TEMPORAL CHANGES IN GAS HYDRATE MOUND TOPOGRAPHY AND ECOLOGY:

DEEP-SEA TIME-LAPSE CAMERA OBSERVATIONS

A Thesis

by

MICHAEL FREDRIC VARDARO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2004

Major Subject: Oceanography

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Approved as to style and content by:

Mahlon C. Kennicutt II (Chair of Committee)	Ian R. MacDonald (Member)
Norman L. Guinasso, Jr. (Member)	Wilford Gardner (Head of Department)

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ABSTRACT

Temporal Changes in Gas Hydrate Mound Topography and Ecology: Deep-sea Time-lapse Camera Observations. (May 2004)

Michael Fredric Vardaro, B.S., Georgetown University

Chair of Advisory Committee: Dr. Mahlon C. Kennicutt II

A deep-sea time-lapse camera and several temperature probes were deployed on the Gulf of Mexico continental shelf at a biological community associated with a gas hydrate outcropping to study topographic and hydrologic changes over time. The deployment site, Bush Hill (GC 185), is located at 27°47.5' N and 91°15.0' W at depths of ~540m. The digital camera recorded one still image every six hours for three months in 2001, every two hours for the month of June 2002 and every six hours for the month of July 2002. Temperature probes were in place at the site for the entire experimental period.

The data recovered provide a record of processes that occur at gas hydrate mounds. Biological activity was documented by identifying the fauna observed in the time-lapse record and recording the number of individuals and species in each image. 1,381 individual organisms representing 16 species were observed. Sediment resuspension and redistribution were regular occurrences during the deployment periods. By digitally analyzing the luminosity of the water column above the mound and plotting the results over time, the turbidity at the site was quantified. A significant diurnal pattern can be seen in both luminosity and temperature records, indicating a possible tidal or inertial component to deep-sea currents in this area.

Contrary to expectations, there was no major change in shape or size of the gas hydrate outcrop at this site on the time frame of this study. This indicates that this particular mound was more stable than suggested by laboratory studies and prior *in situ* observations. The stable topography of the gas hydrate mound combined with high bacterial activity and sediment turnover appears to focus benthic predatory activity in the mound area. The frequency and recurrence of sediment resuspension indicates that short-term change in the depth and distribution of surface sediments is a feature of the benthos at the site. Because the sediment interface is a critical environment for hydrocarbon oxidation and chemosynthesis, short-term variability and heterogeneity may be important characteristics of these settings.

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CHAPTER I
INTRODUCTION AND LITERATURE REVIEW

Gas hydrate is an extremely abundant ice-like, meta-stable compound that forms when gas molecules are concentrated under high pressure and low temperature conditions (Sloan 1998). When the conditions for gas hydrate formation are met, "guest" molecules such as methane and other hydrocarbons become trapped inside a rigid framework of water molecules. The structure and stability of this matrix is determined by the size of the guest molecules. Larger guest molecules enable the hydrate structure to remain stable at higher temperatures. Scientific interest in gas hydrate is in large part due to uncertainty regarding gas hydrate formation, preservation, and dissociation over geologic time (Brooks, et al. 1984; Kennicutt II 1985; Kennett, et al. 2000). Although changes in both temperature and pressure can destabilize gas hydrate deposits, gas hydrate is more sensitive to temperature changes, requiring only a few tenths of a degree increase to induce dissociation (Xu and Lowell 2001). The worldwide gas hydrate reservoir contains a significant amount of carbon, thus the stability of deep-sea gas hydrate deposits may have important implications for climate change that have been widely discussed (Kvenvolden 1988). Some scientists theorize that temperature and ocean current fluctuations caused by global warming and other processes may cause the dissociation of deep sea gas hydrate deposits perturbing the Earth's carbon cycle (Weissert 2000). There is evidence that large-scale dissociation of gas hydrate deposits in the past led to increased warming and climate change (Dickens 1999; Hesselbo, et al. 2000; Weissert 2000; Halverson, et al. 2002). A second school of thought posits that gas hydrate is more stable than predicted and that the water column is so large and the concentration of hydrocarbons so small that any major outgassing due to gas hydrate dissociation would be oxidized and dispersed before reaching the atmosphere (Kvenvolden 1999; Valentine, et al. 2001; Grant and Whiticar 2002; Milkov and Sassen 2003).

All of these theories are based on short-term observation of gas hydrate outcroppings. Long-

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This thesis is written in the style of Geo-Marine Letters.

term, *in situ* observation of gas hydrate sites is logistically challenging due to the water depth and remoteness from land. Gas hydrate is mostly found buried deep in marine sediments being identified only through seismic detection of bottom simulating reflectors (BSRs) (Dickens 2001). The unique geology of the northern Gulf of Mexico continental slope, including thick sediment columns, salt diapirs and active hydrocarbon venting through numerous faults, concentrates hydrocarbon gases in shallow sediments resulting in gas hydrate deposits close to the seawater/sediment interface (Roberts 1995). Gas hydrate has been observed to cap faults and form sizable outcroppings or mounds on the seafloor (Brooks, et al. 1984). In this setting, gas hydrate formations are subjected to variations in temperature and currents (Roberts, et al. 1999). This setting also provides a unique opportunity to study the short-term response of gas hydrate to changing temperatures, water circulation, morphology during growth, and interactions among benthic fauna and bacteria. *In situ* monitoring, consisting of a deep-sea time-lapse camera and several temperature probes, was used to study short-term topographic and ecological processes at a gas hydrate outcrop on the northern Gulf of Mexico continental slope. The detailed time series photographic record complements data recovered from *in situ* sensors providing important confirmation that equipment arrays remain operational during deployments. A review of the literature relevant to this work is provided below.

Literature Review

Gas Hydrate History

Gas hydrate is also known as a clathrate: a rigid structure of host molecules enclosing a "guest" molecule within a crystalline matrix, with no chemical bonding between the host and guest molecules (Sloan 1998). These crystals are normally formed by water molecules under high pressure and low temperature conditions in the presence of sufficiently high concentrations of the enclosed molecules, usually a hydrocarbon gas (Pellenbarg and Max 2000). Three different forms of natural gas hydrate have been documented, with differing stabilities and crystal structures (Kvenvolden 2000). Structure I gas hydrate has a cubic lattice structure large enough to contain methane molecules. It is the most volatile gas hydrate form, freezing at 7°C under 50 atm of pressure (Fig. I-1). Structure II gas hydrate is comprised of diamond-shaped lattices and contains methane, ethane or propane gas. It forms at 17°C under 50 atm and

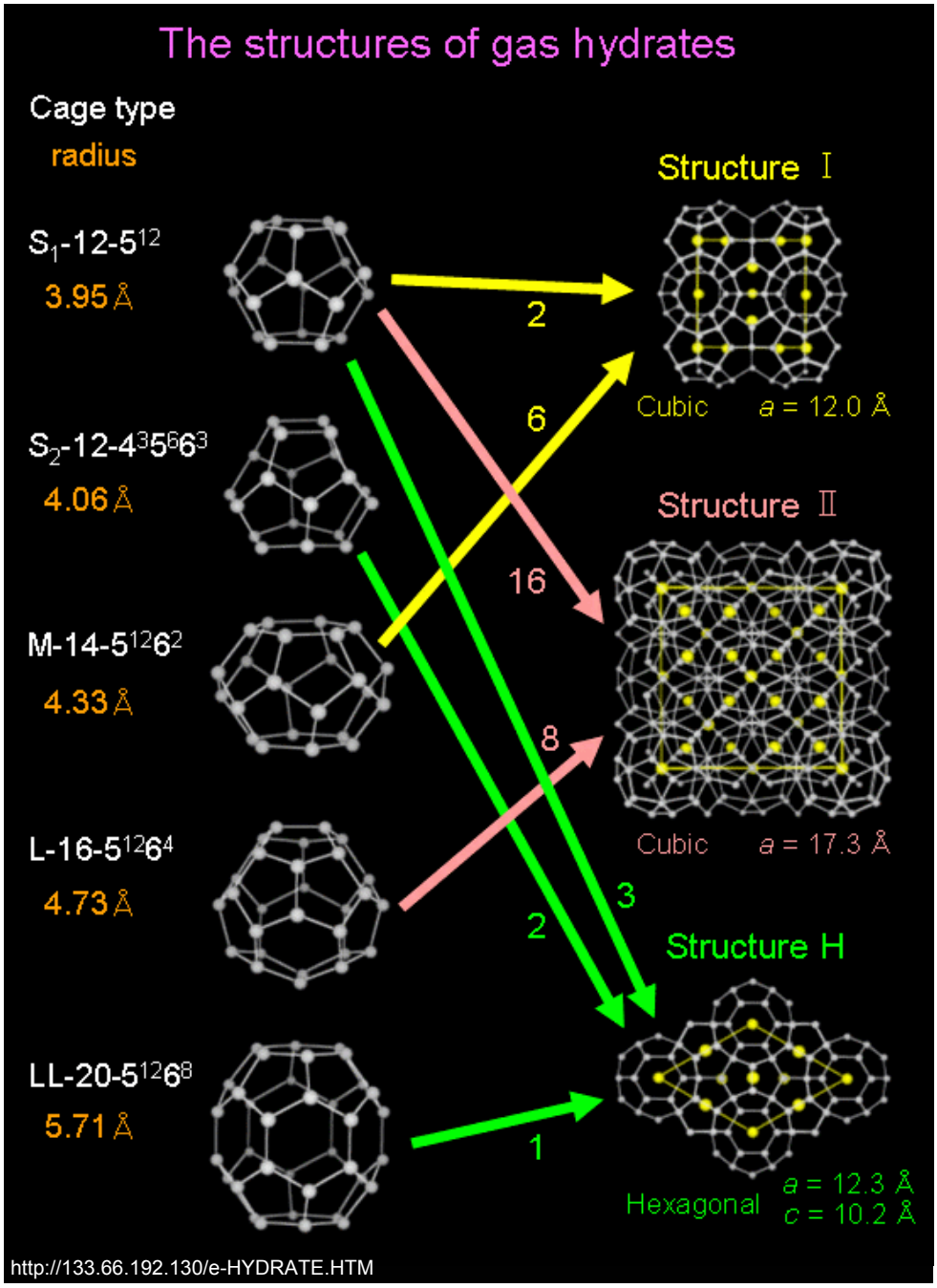

Fig. I-1. The structures of gas hydrate. Hydrocarbon guest molecules become trapped within cages of water molecules under high pressure, low temperature conditions. The water molecule cages on the left combine to form gas hydrate lattices with cubic (structure I), diamond (structure II) and hexagonal (structure H) shapes. Structure I is the least stable form of gas hydrate because it is composed of smaller cages containing low weight hydrocarbons. Structure II and structure H remain stable at higher temperatures because their lattice structure incorporates larger cages and higher weight hydrocarbons.

is found at shallower ocean depths and higher temperatures than structure I. Finally, structure H gas hydrate is a complex of hexagonal crystals containing even larger molecules than the other two forms. However, only structures I and II gas hydrate have been conclusively proven to form naturally at the seafloor. A second form of classification of gas hydrate depends on the origin of the enclosed molecules. If the gas is produced by geothermal heating of source rocks the gas hydrate is identified as "thermogenic" while gas hydrate termed "biogenic" contains gas generated during bacterial metabolic processes (Brooks, et al. 1984). The gas hydrate stability zone (GHSZ) is the area within which the physical conditions for gas hydrate formation exist (Fig. I-2), given sufficient natural gas concentrations (Dillon and Max 2000). The upper limit of the GHSZ is at the ocean floor below depths of between 300 and 400 meters, where appropriate thermal and pressure conditions are present. The seafloor is the absolute ceiling of the GHSZ because seawater is undersaturated with respect to hydrocarbons, and even if saturation point was reached gas hydrate that formed would float away due to its low density (Dickens 2001). The lower limit of the GHSZ depends on the water depth, but is generally no more than 2.5 km deep in the sediment due to the gradual geothermal warming (Dillon and Max 2000).

Natural gas hydrate has been found capping hydrocarbon gas seeps and forming as crystals in sediments throughout the world's oceans, most notably in the Gulf of Mexico, Hydrate Ridge off the coast of northwestern United States, Blake Ridge off the southeastern US coast, Nankai Trough south of Japan, in the Baltic Sea and on the west coast of Africa (Dickens 2001; Milkov and Sassen 2001). Although gas hydrate was recognized as a pipeline-clogging hazard in the 1920's and 30's (Pellenbarg and Max 2000), it was not suspected to occur in nature until the 1970's. The presence of natural gas hydrate was first inferred based on sonar records that exhibited bottom-simulating reflectors (BSRs) and acoustic wipeout zones. A BSR is an acoustic reflection that parallels the seafloor topography, transecting shifts in rock composition and growing deeper as water depth increases (Shipley, et al. 1979). It is theorized to be produced by the base of the GHSZ, where high density, high sonic velocity gas hydrate meets the low sonic velocity free gas beneath it (Stoll, et al. 1971). Acoustic wipeout zones are distinct areas in sonar records that exhibit no sub-bottom echoes and are interpreted to be due to the absorption of sound waves by trapped pockets of gas (Addy and Worzel 1979). While not every BSR or acoustic wipeout zone is

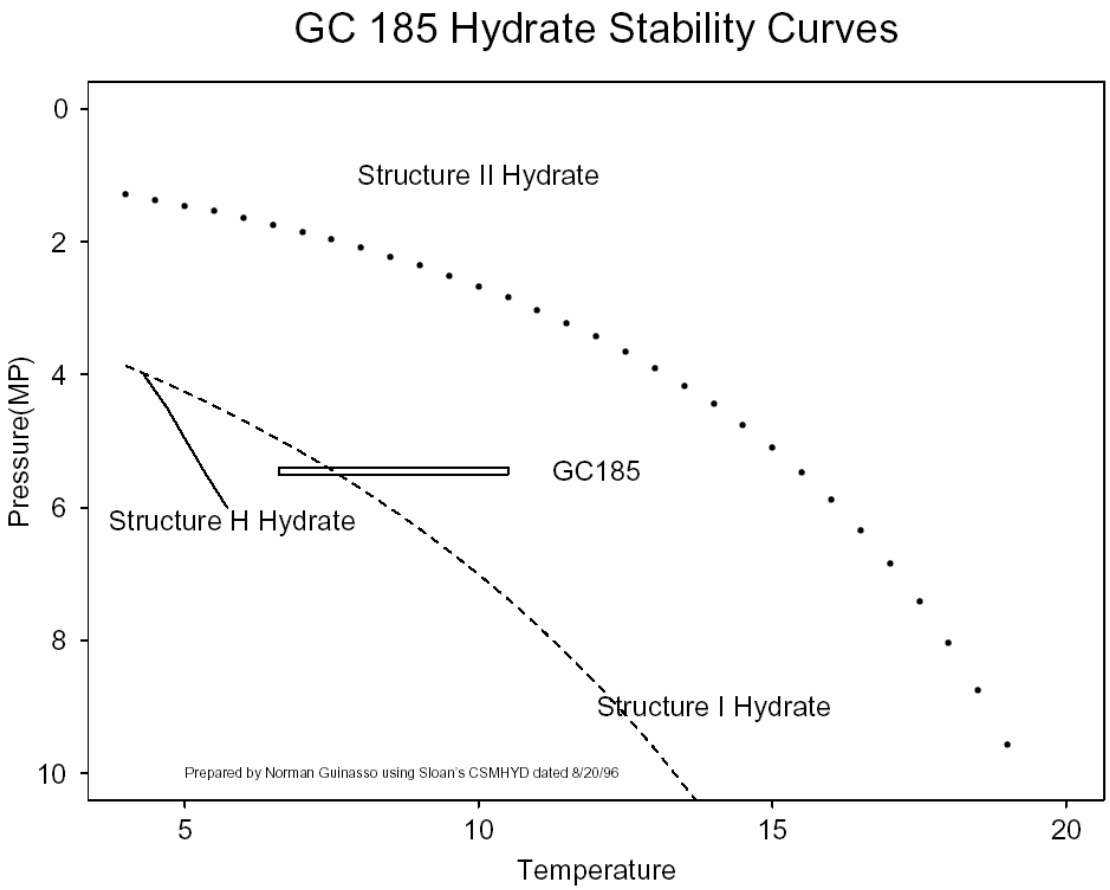

Fig. I-2. The gas hydrate stability zone (GHSZ) curves for structures I, II and H gas hydrate. The stability field for each species of gas hydrate is the area below the corresponding curve. The pressure-temperature region of the site of this research, GC185 (Bush Hill) on the northern continental slope of the Gulf of Mexico, is shown by the box. Given the average pressure and temperature at GC185, structure II gas hydrate is most likely the only stable form of gas hydrate at this site (Guinasso 2001).

caused by the presence of gas hydrate (Ruppel 2000), gas hydrate is often found in association with these sonar features (Sager, et al. 1999). Core samples taken in the Black Sea provided the first observation of gas hydrates in shallow marine sediments, above the BSR zone (Yefremova and Zhizhchenko 1974).

Thermogenic gas hydrate was first discovered in the Gulf of Mexico during piston core surveys in the 1980s (Brooks, et al. 1984). Cores taken from a seismic wipeout zone exhibited intact crystals dispersed throughout the carbonate rock and sediment, from the sediment-water interface to a depth of several meters. The gas hydrate recovered was confirmed to be thermogenic in nature based on isotopic and molecular analyses and the presence of large amounts of oil. Similar methods and the relative abundance of the gases produced during dissociation confirmed the gas hydrate was present as structure II. The continental slope in this area has very complex bathymetry caused by geologic forces and ongoing processes such as sediment slumping, salt diapirs and extensive faulting (Bouma, et al. 1981). Although gas hydrate is most often found buried deep in marine sediments (Dickens 2001), the unique geology and geologic history of the Gulf of Mexico results in gas hydrate forming closer to the sediment/water interface providing the opportunity for *in situ* observations (Milkov and Sassen 2000). Subsequent cores and submersible operations have discovered thermogenic and biogenic gas hydrate at many sites along the Gulf of Mexico continental slope (Brooks, et al. 1985). Biogenic gas hydrate appears to form near the seafloor as small, white crystals dispersed in the sediment. Thermogenic hydrocarbon gases travel through faults to the seafloor and form masses of oil-stained gas hydrate when the temperature is low enough to be within the GHSZ, generally in water depths greater than 400 meters (Anderson, et al. 1992). The thermogenic gas hydrate found in the Gulf often forms sizable lenticular outcroppings or mounds that breach the seafloor (MacDonald, et al. 1994; MacDonald, et al. 2003). Significant amounts of oil and authigenic carbonate rock are also found associated with most gas hydrate deposits (Brooks, et al. 1985) and large amounts of free gas form bubble plumes that intermittently or continually flow from the seafloor (Sassen, et al. 1993a). This episodic fluid and gas expulsion can occur at varying rates, depending on the size of the fault and subsurface features (Roberts and Carney 1997). At the most degassing sites, the plumes are often thick enough to be visible on acoustic profile traces and produce acoustic shadows on

side-scan sonar records (De Beukelaer, et al. 2003). It was also discovered that chemosynthetic communities are associated with many of the gas hydrate sites in the Gulf of Mexico (Kennicutt II 1985).

Seep Communities

Once believed to be a barren, static environment, devoid of life, the deep ocean has been revealed as a biologically diverse and constantly changing region of the earth (Sanders 1968). Hydrothermal vents at the Galapagos Rift and East Pacific Rise were first found to support colonies of tube worms and bivalves in 1977 (Corliss, et al. 1979). Communities with remarkably similar anatomic and physiologic characteristics have since been documented at other hydrothermal vents and cold seeps worldwide (Paull, et al. 1984; Kennicutt II 1985; Suess, et al. 1985; Barry, et al. 1996; Olu, et al. 1996; Van Dover, et al. 2003), and there is genetic evidence for a shared evolutionary history between vent and seep species (Olu, et al. 1996; Van Dover, et al. 2002). Although both vent and seep sites are much higher in biomass than background benthic environments, communities at cold seeps have been found to be higher in diversity than those at hydrothermal vents, possibly due to the higher stability, lower stress and less-isolated nature of cold seeps (Sibuet and Olu 1998; Turnipseed, et al. 2003). The reduced compounds contained in the oil, gas hydrate and free gas escaping at cold seep sites are utilized by symbionts found in a number of the organisms that inhabit seep communities (Cavanaugh, et al. 1981; Felbeck 1981). The distribution of chemosynthetic fauna appears to be related to spatial and temporal variations in the supply of sulfide, methane and oxygen. The transition between the surrounding environment and seep communities is often abrupt (MacDonald, et al. 1989).

The biological community inhabiting gas hydrate mounds consists of many different populations, exhibiting several trophic levels. Orange (pigmented) and white (non-pigmented) *Beggiatoa* bacterial mats, up to several meters across, often cover the sediment and gas hydrate surface (Barry, et al. 1996). Recent metabolic tests show that differences in *Beggiatoa* pigmentation may connote differences in trophic strategies. While non-pigmented *Beggiatoa* appear to be autotrophic, oxidizing sulfide carried upward by oil and gas seeps, lack of RuBisCO activity and carbon fixation in the pigmented type indicates that the cells are heterotrophic, directly oxidizing hydrocarbons or other organic compounds to obtain

energy and carbon (Nikolaus, et al. 2003). The mats may also act as a physical barrier that slows the escape of hydrocarbons and other fluids from the sediment (Sassen, et al. 1993c). Other bacteria and *Archaea* appear to oxidize hydrate-bound carbon and methane gas in the sediment, freeing it for use by other species and precipitating carbonate rock (Sassen, et al. 1998; Sassen, et al. 1999; Lanoil, et al. 2001; Zhang, et al. 2003). Considering the numbers and diversity of the sediment microbial community, anaerobic methane oxidation may be the most dominant bacterial process in Gulf of Mexico gas hydrate ecosystems (Mills, et al. 2003). Vestimentiferan tubeworms (*Escarpia* spp. and *Lamellibrachia* spp.) are annelid-like organisms with no mouth, gut or anus that inhabit semi-rigid tubes composed of secreted chitin contained in a protein matrix and aggregate in large, intertwined bundles at cold seep sites. Tubeworms contain chemoautotrophic bacteria that utilize H_2S, O_2 and CO_2 to produce the energy that sustains both the bacteria and the host (MacDonald, et al. 1989). These tubeworms are one of the most numerous faunal types found at cold seep sites in the Gulf of Mexico. By extracting sulfide from interstitial water in the sediment through buried "roots," tubeworms reduce the toxicity of the surrounding environment, enhancing community diversity and providing shelter for other organisms (Julian, et al. 1999; Cordes, et al. 2003). Polychaete worms (*Hesiocaeca methanicola*) live directly on and in the gas hydrate itself, forming burrows and tunnels in the gas hydrate mass. Since dissection and microscopic surveys have found no evidence of internal or external symbionts, the "ice worms" may feed on bacterial matter found in the hydrate (Fisher, et al. 2000). However, this has not been confirmed by isotopic analysis. *Bathymodiolus* mussels and *Vesicomya* clams, some heterotrophic and some with methane-oxidizing endosymbionts, form large beds in seep areas (MacDonald, et al. 1989).

The chemolithotrophic processes and aggregations of cold seep producers provide oxidized compounds and a habitable environment for secondary consumers to inhabit the seep. Biogenic structures such as tubeworm bushes and mussel beds provide food, living space, colonization substrate, and sanctuary from predation and stressful agents (Bergquist, et al. 2003). Stable isotope and radiocarbon analysis have proven that some organisms are obligate seep endemics and colonists, restricted by metabolic or dietary needs to the area around the seep, while others are vagrant predators that move freely in and out of the seep region (Carney 1994; MacAvoy, et al. 2002). A number of species of non-

chemosynthetic organisms such as certain fish and eels, snails (*Buccinum canetae*), shrimp (*Alvinocaris*), sea stars (*Sclerasterius*), and Atelecylid crabs feed almost entirely on chemosynthetic organisms. MacAvoy also showed that other large predators like hagfish (*Eptatretus*), spider crabs (*Rochinia crassa*), and isopods (*Bathynomus gigantus*) migrate in and out of the gas hydrate community, feeding on chemo- and photosynthetic species. The macrofaunal species composition appears roughly the same at all Gulf of Mexico seep sites; however, when site depth and region are taken into account, greater differences emerge (Carney 1994). Morphologically similar but genetically distinct chemosynthetic and associated consumer species are found at seep sites in different regions and depths on the Gulf slope (Bergquist, et al. 2003; MacDonald, et al. 2003). All of these organisms ultimately depend on the availability of hydrocarbon gases evolving from the sediment and gas hydrate mounds. If a large amount of gas hydrate were to break free or dissociate due to changing water temperatures, the population dynamics of this ecosystem might shift. Less substrate would be available to attach to or burrow in, and the amount of chemical energy available to the system would be dramatically decreased.

Gas Hydrate Stability and Ecological Significance

Since its discovery, gas hydrate has been viewed as a potential hazard to oil drilling, a possible energy source, and as a habitat for chemosynthetic communities (Kvenvolden 1999). Another area of interest is the effect of large-scale gas hydrate dissociation in marine settings on climate. Depending on the structure and conditions of formation, a given quantity of gas hydrate can contain up to 164 times the amount of gas at STP (Sloan 1998). The total quantity of carbon that is sequestered in gas hydrate form is unknown, but it is estimated to be about 1×10^4 Gigatons (Kvenvolden 1988). Even more conservative estimates confirm that gas hydrate is a reservoir of methane thousands of times greater than the amount found in the atmosphere. This is significant because methane is an important greenhouse gas trapping solar energy and contributing to global warming (Kvenvolden 1999). It has been observed that as water temperature increases gas hydrate begins to dissociate, releasing trapped gas (MacDonald, et al. 1994). Dissociation of gas hydrate may also occur due to tectonic events and sediment slumping that reduce overburden pressure. This is illustrated by disrupted areas in seismic signatures at a gas hydrate ridge off

the Oregon coast (Trehu, et al. 1999). If global warming results in an increase in global ocean temperatures, or if a seismic event destabilizes a large gas hydrate reservoir (Fig. I-3), it could result in the release of gas hydrate-bound methane into the water column and possibly the atmosphere (Peltzer and Brewer 2000; Weissert 2000). This event could then lead to even greater warming (Dillon and Max 2000). Sea levels would rise as a result of density effects and polar ice melting. The resulting increase in the amount of fresh water released into the ocean could disrupt the global conveyor belt that distributes heat, causing worldwide climate change (Stewart 2001). While this progression of events is speculative, the outcome would be devastating.

There is indirect evidence that gas hydrate outgassing has occurred in the past, and be responsible for the observed climate changes (Dickens 1999; Hesselbo, et al. 2000; Weissert 2000; Halverson, et al. 2002). Proxy indicators; biological, chemical or physical "fingerprints" in the geologic record that trace the evolution of the biosphere; point to several historical perturbations in the Earth's atmosphere that may be gas hydrate-related (Weissert 2000). Fossilized wood deposits indicate that such elevated carbon-isotope signals occurred during a known alteration in the marine carbon reservoir in the Toarcian Stage of the Jurassic period, approximately 183 million years ago (Hesselbo, et al. 2000). Previous studies have shown that gas hydrate is enriched in ^{12}C-containing hydrocarbons (Kvenvolden 1993), and gas hydrate is one of a small number of sources that could release the required amounts of carbon over a few thousand years during these anomalies (Norris and Rohl 1999; Dickens 2001). Multiple sediment cores collected during Ocean Drilling Project (ODP) cruises (Dickens 1999; Norris and Rohl 1999) show large changes in the ratio of ^{13}C to ^{12}C during periods in the Late Paleocene Thermal Maximum (LPTM), about 55 million years ago. Isotopic analyses of polar ice-cores exhibit oscillating levels of atmospheric methane that track climate cycles in the Quaternary period (Kennett, et al. 2000). These cycles may be related to the extent of wetlands or marshes (McQuoid, et al. 2001), but could also be related to gas hydrate effects.

Several seafloor formations in present-day gas hydrate deposits suggest that modern gas hydrate may be unstable. Pockmarked sediment fields and eruptive craters in the Barents Sea and Storegga Slide in Norway have been theorized to be evidence of recent gas hydrate destabilization and the rapid release of pressurized gas (Mienert and Posewang 1999). Mineralogical study of hydrate-associated carbonate

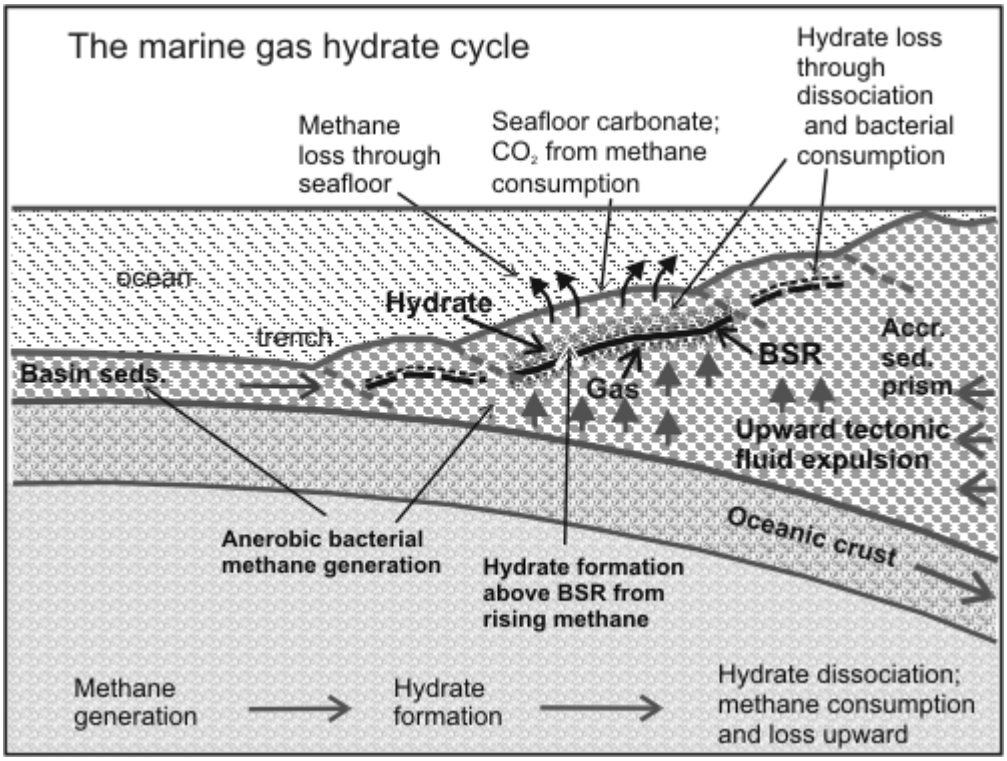

Fig. I-3. A simplified cartoon of the gas hydrate cycle. This figure illustrates the path of gas hydrate-bound hydrocarbons from bacterial or thermogenic sources to the atmosphere. As gas hydrate dissociates due to warming or sediment slumping, gas is released into the water column and eventually the atmosphere. If enough methane and carbon dioxide are released, it would greatly increase the amounts of greenhouse gases in the atmosphere and possibly cause climate change (www.pgc.nrcan.gc.ca/marine/gas_hydrates).

phases in the Blake Ridge region indicate that massive deposits of gas hydrate have undergone periodic destabilization (Bohrmann, et al. 1998). However, some scientists doubt that gas hydrate has the power to affect the balance of atmospheric gases. Recent studies of methane concentrations above known cold seeps appear to indicate that most of the methane released from gas hydrate dissociation is converted to carbon dioxide and sequestered by chemical or biological means before it ever reaches the atmosphere (Kvenvolden 1999; Valentine, et al. 2001; Grant and Whiticar 2002; Milkov and Sassen 2003). Conversely, methane might directly enter the atmosphere if sediment slumping caused the release of large, buoyant crystals or nodules of gas hydrate that travel through the water column nearly intact before dissociating at the air/sea interface (Paull, et al. 2003). Hydrocarbons could also be transported to the surface by bubble plumes via a gas hydrate "skin" that can form around bubbles of natural gas or within highly stable, oily bubbles (MacDonald, et al. 2002). Certain experts on climate change assert that plate tectonics, ocean currents and orbital cycles all have greater impact on global climate than atmospheric carbon dioxide or methane levels (Harris 2002). Others theorize that gas hydrate is more stable than prior researchers have concluded based on volume measurements and the differences between the carbon composition of gas hydrate and vent gas samples (Sassen, et al. 2001a; Sassen, et al. 2001b; Sassen, et al. 2001c). According to this premise only a thin "skin" of exposed surface at the sediment-water interface is prone to dissociation and the rest of the mass is protected from temperature change and bacterial attack by burial in sediments.

The Gulf of Mexico is an ideal location to observe short-term processes at small spatial scales. The relatively shallow water, warm loop currents, and widespread faulting allow warm water to reach the gas hydrate surface with more regularity than at other gas hydrate locations. Mounds in the Gulf of Mexico have been observed to change shape in less than a year, with lobes intermittently being undercut and breaking off, disturbing the sediment and exposing fresh gas hydrate (MacDonald, et al. 2003). Temperature probes, current meters, and bubblometers (which measure the rate of gas released from a seep using a rotating chamber) placed at a site known as "Bush Hill," or GC 185, have shown that diurnal and semiweekly pulses of north-south current can warm the bottom water by 2-3°C, with corresponding increases in gas emissions (Roberts, et al. 1999). However, the actual process of hydrate dissociation

during one of these warming events has not been directly observed or quantified. The exposed nature of the gas hydrate and the frequency and intensity of the temperature variations in this area make it an ideal site to study the effects of seawater warming on gas hydrate stability over short periods of time.

History of Bush Hill

Green Canyon lease block 185 contains one of the most visited and well-documented hydrocarbon seep communities and gas hydrate study areas on the Gulf of Mexico continental slope. It has also coexisted with oil production platforms and activity in Jolliet field since 1989 (MacDonald, et al. 2003). Located approximately 100 miles south of the Louisiana coast (27°47.5' N and 91°15.0' W), the site was christened Bush Hill because of its topographic relief and the presence of several large aggregations of tubeworm "bushes". The site itself is a 500 m wide mound of mud rising about 40 m above the seafloor and associated with several large north-south antithetic faults (Sassen and MacDonald 1994). The gas and oil flowing upward through these faults infiltrate the sediment, escaping into the seawater via bubble plumes (Sassen, et al. 1993b). Carbonate rock, precipitated during the bacterial oxidation of the hydrocarbons, forms a stable substrate for tubeworms, mussels, gorgonians and other colonial organisms. Water temperature at the site is ~7° C and mean sea-bottom pressure is ~5,400 kPa. It has been shown under these conditions that structure II gas hydrate crystallizes rapidly when sufficient quantities of hydrocarbon gases are present (Sassen and MacDonald 1997). Gas hydrate outcroppings form around the gas vent, occurring as large, solid masses or mounds rather than isolated seams or nodules. A large number of these mounds can be found at the crest of Bush Hill, and can be 30-50 cm high and several meters in diameter. Some have also been shown to persist at the same location for more than 5 years, while others dissociate or break free and disappear within months (MacDonald, et al. 2003). Although the mounds are mostly covered by a thin layer of sediment, yellow-orange gas hydrate is often visible along the flanks and base (MacDonald, et al. 1994). There are many other gas hydrate sites in the Gulf of Mexico; however, Bush Hill's relatively shallow depth, large size, active venting and thriving seep community have made it a site of intensive study.

First discovered during piston coring operations in the 1980's (Brooks, et al. 1985), Bush Hill has been visited often since by the U.S. Navy submersible NR-1 and the Johnson Sea-Link submersible, operated by Harbor Branch Oceanographic Institute. Extensive surveys of the site, and the community it supports, have been conducted by visual inspection, video and still photography and sidescan sonar (MacDonald, et al. 1989; MacDonald 2001). Vent gas and gas hydrate samples have been retrieved and analyzed to determine the origin and amount of degradation of fossil carbon (Sassen and MacDonald 1997). Seep organisms and roaming predators have been collected for identification and tissue analysis to determine trophic linkages (Carney 1994; MacAvoy, et al. 2002). Long-term studies have been limited to comparing seep feature evolution during yearly visits (MacDonald, et al. 1994) or leaving remote devices such as temperature probes and chambers that measure gas volume to detect changes in gas emissions (Roberts, et al. 1999). Little is known about the real-time processes that occur at the site and the mechanism of gas hydrate dissociation is still mostly conjectural. Time-lapse photography by means of long-term deployments of deep-sea camera equipment, such as the array used in this study and recent work by Macdonald, et al. (MacDonald, et al. 2003), is intended to provide continuous observations on the time frame of minutes to months.

Deep-sea Time-lapse Photography

Marine biologists and geologists have used deep-sea photography to identify objects of interest in the deep ocean since the late 1960s (Ewing and Davis 1967; Menzies, et al. 1973; Grassle, et al. 1975; Lemche, et al. 1976). However, with the exception of a baited "Monster Camera" used by Isaacs in 1975, all of these deployments were instantaneous snapshots of the seafloor. It wasn't until 1974 that a long-term alternative was developed when Gerard and Thorndike created the Bottom Ocean Monitor (BOM). This device consisted of a time-lapse film camera and a Thorndike photographic nephelometer mounted on a tripod, with a current meter and temperature recorder attached above them. The equipment was deployed for 202 days and took pictures of the ocean bottom every 4 hours (Paul, et al. 1978). Significantly more information about the mechanism and rates of deep-sea processes was collected by

adding a time dimension to the photographic record. The experiment also illustrated how little was known about the dynamic benthic environment.

Important data on deep-sea processes as well as the costs of operating research vessels and submersibles over the ensuing years has led to greater reliance on *in situ* monitoring devices such as time-lapse cameras and video systems. Operation of this equipment presents its own difficulties such as lens fouling by bacteria and other organisms and burial in sediments during the long deployment periods in these environments. Video cameras are inexpensive and easy to use, but have generally lower resolution compared to still cameras and require more data storage capacity (Carter, et al. 1979). Despite the drawbacks and because of the advantages over video, time-lapse photography has become the method of choice for long-term deep-sea studies. Observations and measurement of coral growth rates (Barnes and Crossland 1980), deep ocean floor processes (Thorndike, et al. 1982; Gardner, et al. 1984), feeding rates of abyssal scavengers (Hargrave 1985; Ramsay, et al. 1997), and the behavior and mortality of hydrothermal vent tubeworms (Tunnicliffe, et al. 1990) and gastropods (Martell, et al. 2002) are only a small sample of the scientific applications of time-lapse photography. The rise of digital photography as a cheap and efficient alternative to more time-consuming and delicate film cameras has further extended the utility of this tool.

Deep-sea Currents

One of the surprising discoveries made possible by remote sensing and time-lapse photography is the high degree of water movement and turbulence at the seafloor, even in deep waters. Although early suppositions characterized the deep-sea environment as a featureless, unchanging plain of mud (Sanders 1968), more recent evidence, including time-series images from sleds and instrument arrays, have shown that this view is incorrect (Gardner and Sullivan 1981; Billett, et al. 1983). One of the first studies to report large-scale benthic disturbances was conducted in 1977, using a long-term nephelometer (LTN) to measure concentrations of suspended particulate matter in the western North Atlantic ocean at depths of nearly 5000m (Gardner and Sullivan 1981). The record that was recovered showed rapid and intense variations in light scattering due to the suspension of sediment by bottom currents. These events were so

extreme that they were termed “benthic storms”. During the early 1980s time-lapse photographic records from 2000m deep in the north-east Atlantic provided evidence of seasonal variations in transport of material to the seafloor, as well as tidal currents that were observed redistributing sediment and detritus (Billett, et al. 1983). Rapid sedimentation and subsequent resuspension has been shown to be a common occurrence in benthic areas below high surface productivity (Lampitt 1985). Local subsurface features have also been shown to affect deep-sea currents and sediment suspension. Transmissometers and time-lapse photography in Baltimore Canyon in the Atlantic demonstrated that oscillatory flows through the canyon were strong enough to lift recently deposited material into the bottom water on a regular basis (Gardner 1989b). It was also theorized that density inversions as cooler water moved over warm sediment pore water could augment sediment suspension (Gardner 1989a).

Most deep currents in the Gulf of Mexico generally originate from energy supplied by the Loop Current and the eddies that detach from it as it moves clockwise from the Straits of Yucatan to the Florida Straits (Brooks 1984; Sheinbaum, et al. 2002). Moored current meters in the Gulf have observed both topographic Rossby waves and periodic inertial currents formed by interactions between the shelf and the loop currents (Hamilton 1990; Hamilton and Lugo-Fernandez 2001). Other studies have recorded tidal currents along the northern Gulf of Mexico continental slope that appear unrelated to Loop Current activity (DiMarco and Reid 1998; Wiseman and Roberts 1999; Guinasso 2001). While the currents recorded during these studies appear insufficiently intense (only a few cm/sec) to resuspend sediment, there is evidence of topographic steering and intensification due to bottom features as well as local large-amplitude thermal fluctuations. Diurnal tidal currents in the Gulf also exhibit seasonal variations, with a substantial increase during the summer months, although these are more pronounced in surface waters than at depth (DiMarco, et al. 2000). Recent submersible surveys of the deep continental slope have uncovered extensive erosional furrows in the seafloor, apparently caused by abyssal currents that accelerate after encountering the steep topography of the Eastward Scarp, the northeastern boundary of the Bermuda Rise (Laine, et al. 1994). Although these furrows occur at much greater depths than dealt with in this study, they demonstrate the variability and power of deep-sea currents and the effects of topography on water movement at depth which directly relate to the data gathered during this research.

CHAPTER II

MATERALS AND METHODS

GC 185, or "Bush Hill", is located southwest of the Mississippi Delta (27°47.5' N and 91°30.5' W) at ~550m depths and contains numerous hydrocarbon seeps, active gas vents and several gas hydrate formations. The gas hydrate occurs in structure II configuration (Sassen and MacDonald 1994) that contains large amounts of oil, sediment and other organic impurities (MacDonald, et al. 2002). Lenticular gas hydrate mounds capping the seeps provide energy and substrate for biological colonization by bacteria and metazoans (MacDonald, et al. 1994). The monitoring period ran from July, 2001 to July, 2002. The monitoring array deployed at the site included a digital time-lapse camera, recording thermistors and several scale markers. The time-lapse camera was a SeaSnap 990 consisting of a modified Nikon CoolPix® 990 camera held inside a pressure-tested housing mounted on an aluminum frame (Fig. II-1). Illumination was provided by two 12 volt, 50 Watt halogen lamps. The camera and lights were triggered simultaneously by a Harbortronics Digisnap® 2500 remote shutter release. System power was delivered by two 12-volt batteries, connected in series in a deep-sea housing filled with mineral oil. Two spherical Iceplast® floats, each with 7 lbs. of buoyancy, were attached to the top of the camera frame for stability. The temperature probes deployed at the site consisted of two Antares® High Resolution Temperature Data Loggers (or thermistors) enclosed in a wand constructed of 2cm PVC pipe (Fig. II-2). By measuring changes in the electrical conductivity of the sensor tip, the thermistors record changes in temperature with ±0.1 °C accuracy and can store 65,000 data points in internal memory. The 53cm-long probes were constructed so that one thermistor sensor tip protruded from each end, allowing ambient water and within-hydrate/sediment temperatures to be simultaneously recorded. A reflective, numbered marker was attached to the top of each probe by a short length of polypropylene line.

The camera and temperature probes were first deployed at the site on 18 July 2001 by the Johnson Sea Link (JSL) submersible, a battery-powered vehicle carrying two scientists and two crew members. The JSL is operated by the Harbor Branch Oceanographic Institute and is launched from the

Fig. II-1. The time-lapse camera deployed at Bush Hill. The spherical floats provided compensating buoyancy and a righting moment, and illumination was provided by the two halogen lamps on either side. The camera was protected by the pressure housing at center. Power for the camera and lights was drawn from the battery case at bottom.

Fig. II-2. Example of temperature probes deployed at the site. A length of PVC tubing (left) contained two thermistors (right) at the top and bottom, with holes to allow the sensor tips to protrude out. Each probe was approximately 50cm long, with a reflective marker float attached by a short length of line.

R/V Seward Johnson. The camera was positioned facing slightly east of due north, approximately 1 m from the edge of a gas hydrate outcrop with 65 cm of relief and about 2.5 m across. This mound had been pre-selected during previous JSL dives because it was close to a bubble plume, large enough to have distinctive features and support a seep ecosystem, yet small enough to be fully visible in the camera's field of view (Fig. II-3). One 1,024 x 756 pixel picture was taken every six hours. The lens aperture was fully closed (F 7.0) to focus the camera over a wide area and a deep field. The auto-shutter was set to change the length of exposure time depending on the light intensity. The zoom was pulled back to provide the widest possible field of view short of a panoramic view. Two plastic markers were positioned on the far side of the mound from the camera to provide scale and to detect changes in mound height. One marker was about 35cm square, and the other was 15cm wide and 1m high, and both markers were anchored by lead weights. The temperature probes were positioned to appear within the camera's field of view. A specialized gas hydrate drill powered by the JSL hydraulics was used to bore a 2cm wide, 7cm deep hole in the hydrate mound, allowing one thermistor probe to be inserted into the mound with a tight seal. A second probe was thrust 50cm into the sediment at the base of the mound, leaving the top thermistor exposed to the overlying water. *In situ* hydrate and sediment temperatures as well as ambient water temperatures were recorded at 30-minute intervals.

The camera was recovered on 6 June 2002. The batteries were recharged and the camera was sited near the same location on 11 June 2002. The camera was facing an angle slightly farther north than it had been during the previous deployment. One photograph was taken every 2 hours at 2048 x 1536 pixel resolution. New thermistor probes, programmed to record one measurement every 70 seconds, replaced those deployed in 2001. One was placed in a freshly drilled hole in the gas hydrate that was 8cm deep, and one that was 16cm deep in sediment that covered a nearby bubble stream. The camera and thermistors were reclaimed for the final time on 3 July 2002.

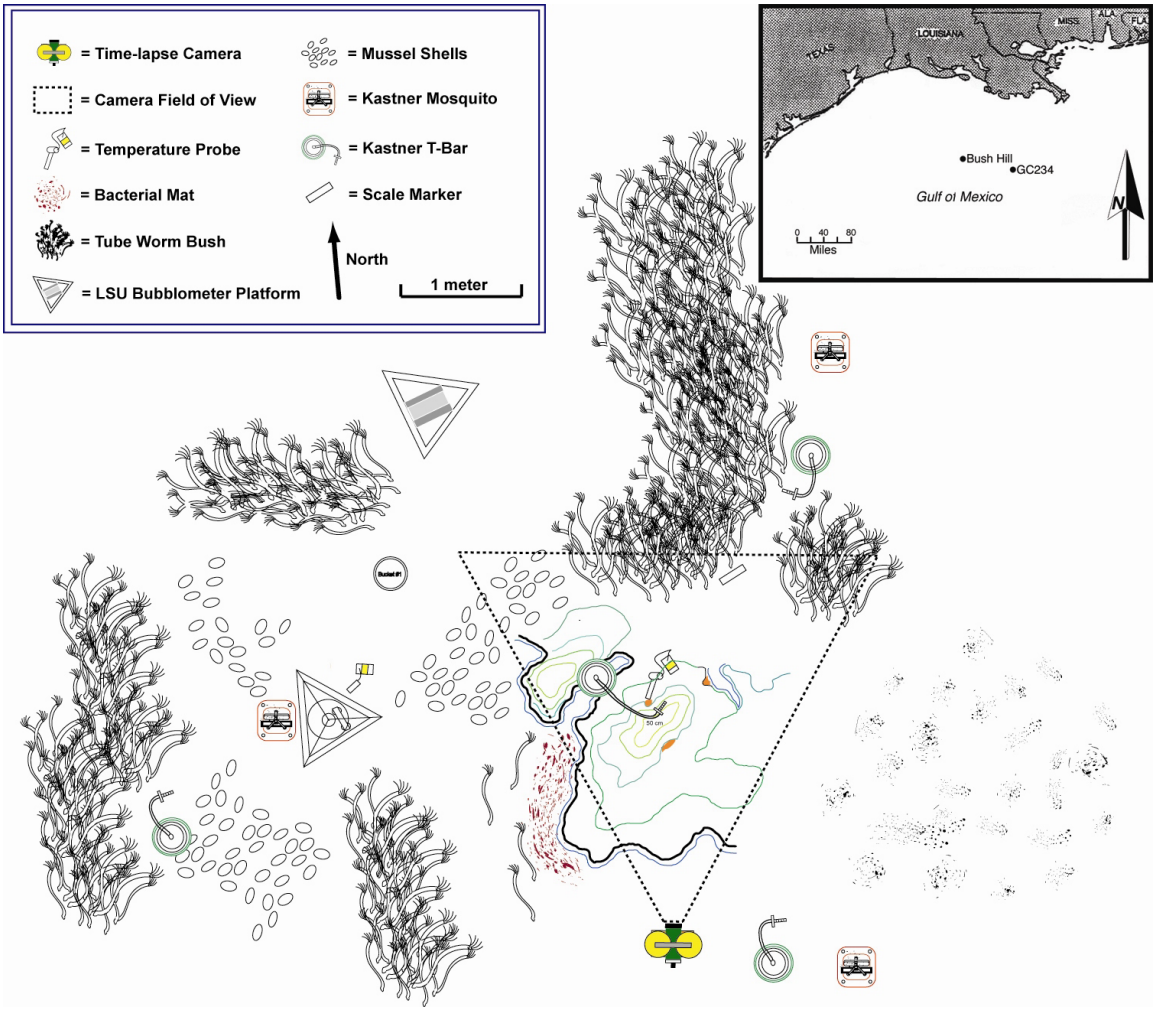

Fig. II-3. Map of camera deployment site at Bush Hill (GC 185, shown on inset map at top right) as it appeared in June 2002. The map was drawn by using photomosaics assembled from video footage of submersible overflights. The hydrate mound has an irregular shape and about 50cm of relief. All of the equipment shown, except for the bubblometer platforms, has since been recovered.

CHAPTER III

TOPOGRAPHIC CHANGES IN THE GAS HYDRATE OUTCROP

Introduction

The major goal of this research was to document physical changes in a gas hydrate outcrop over time. Using time-lapse photographic records and temperature probes, it was intended to confirm the relationship between water temperature increases and gas hydrate dissociation. However, only a small amount of change in the shape and size of the gas hydrate mound was observed during the deployment period by the monitoring array at Bush Hill. The lack of major transformation in the site was unexpected. A number of geological processes were captured indicating how gas hydrate outcrops form, grow and evolve at cold seeps.

Results

The battery power to the camera and lights lasted 91 days during the first deployment, providing 373 images. The field of view for the images included the southern face of the gas hydrate mound, both thermistor probes, scale markers, sediments, several patches of exposed gas hydrate, and bacterial mats and epifauna that colonized the area. The shorter deployment in 2002 lasted 23 days and produced 261 high-resolution images. The internal clock of the camera was verified after recovery and showed negligible (1-2 seconds) drift. Two separate time-series of water, gas hydrate and sediment temperatures were recovered by the thermistor probes (Fig. III-1). During the longer deployment each thermistor recorded 15,693 data points over 327 days. The one-month deployment provided a higher resolution data set with 31,171 temperature readings per thermistor. The results are summarized in Table III-1. Despite periodic fluctuations in water temperature, ranging from 6.59°C to 9.72°C, no bubbling or dissociation of

Table III-1.
Data recovered from remote sensing equipment

Remote Sensing Device	Deployment Period	Sampling Frequency	Data Collected	Results
Time-lapse Camera	91 days (7/01 -10/01)	6 hours	373 images, 1,024 x 756 pixels	Intermittent sediment resuspension. 1,380 individual organisms representing ~20 species observed
	23 days (6/02 - 7/02)	2 hours	261 images, 2048 x 1536 pixels	Gas hydrate appears stable and no dissociation was seen
Temperature Probe #1 (in hydrate)	327 days (7/01 - 6/02)	30 min.	15,693 data points	Min. Water Temp. = 6.59°C Max. Water Temp. = 9.72°C Avg. Water Temp. = 7.85°C
	23 days (6/02 - 7/02)	70 sec.	31,171 data points	
Temperature Probe#2 (in sediment)	327 days (7/01 - 6/02)	30 min.	15,693 data points	Min. Water Temp. = 6.59°C Max Water Temp. = 9.66°C Avg. Water Temp. = 7.86°C
	23 days (6/02 - 7/02)	70 sec.	31,171 data points	

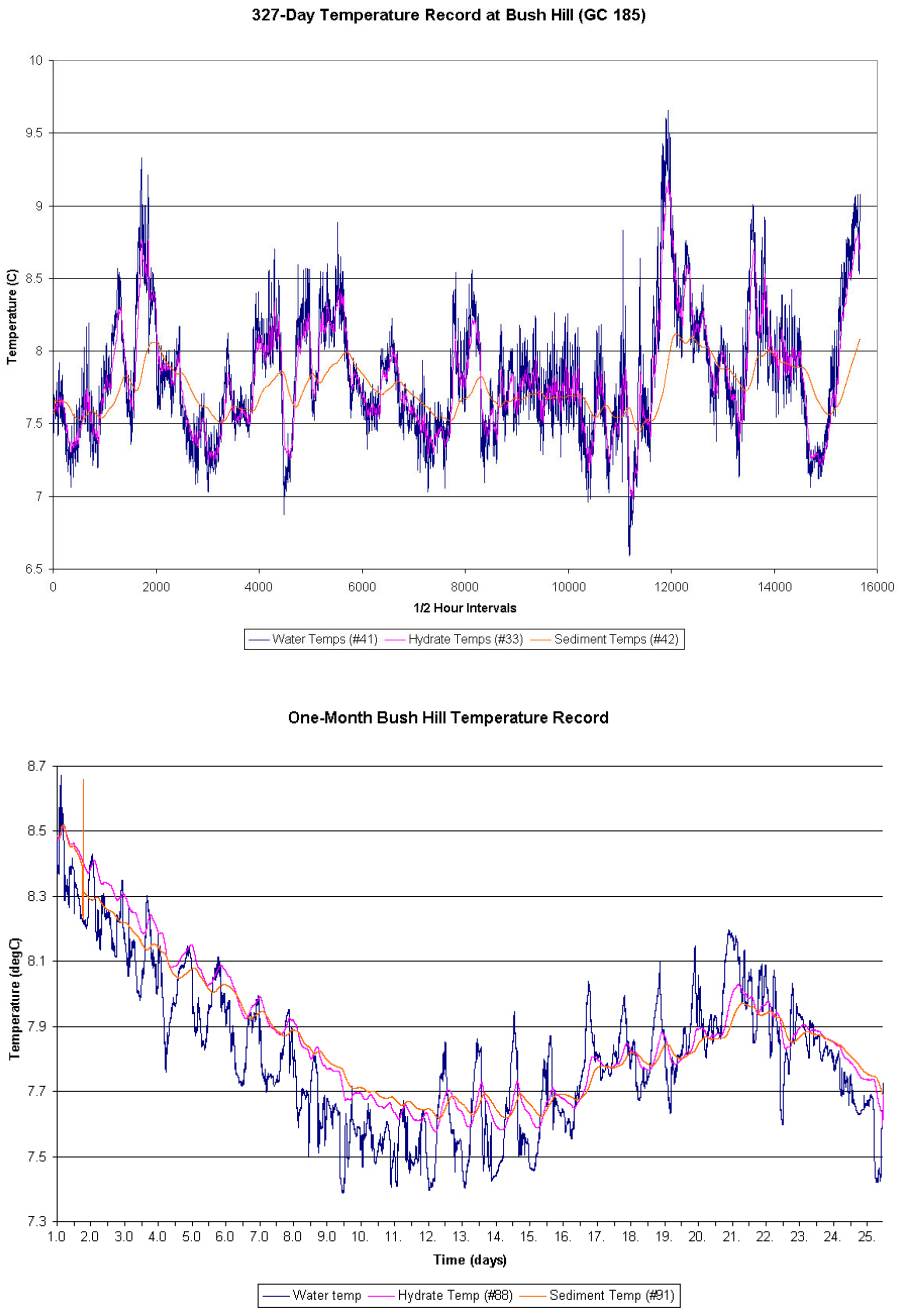

Fig. III-1. Charts of water temperatures (in blue) over the two deployment periods. The greatest change was over 3°C in the year-long deployment and slightly more than 1°C during the second, one-month deployment. The cyclic nature of the temperature changes is evident in both records, while the year-long record also exhibits larger scale variations. Internal gas hydrate and sediment temperatures (in orange and pink) were recorded for a separate heat flow study.

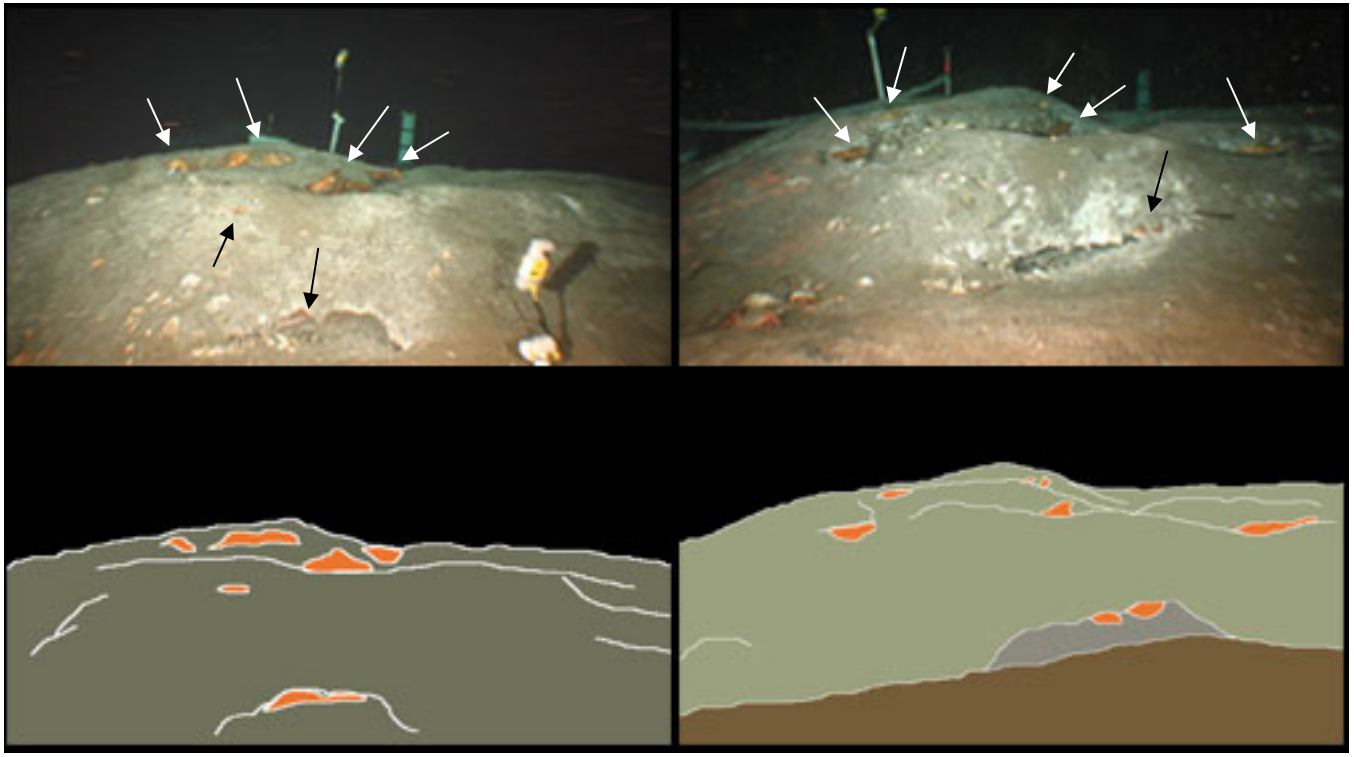

Fig. III-2. Time-lapse photographs taken just after the first camera deployment (top left) and at the end of the second deployment (top right) exhibit very few changes. Aside from a slight shift to the southwest in camera placement, both photos and line drawings (bottom, left and right) show that the gas hydrate mound has the same shape and exhibits only a slight change in elevation. The undercut area in the foreground has widened and deepened slightly, and the sediment cap covering the mound has been redistributed to cover some gas hydrate and expose other patches (exposed hydrate indicated by arrows). Some of the crevices and areas of exposed gas hydrate may be evidence of growth and cracking of the mound.

gas hydrate was observed in the photographs and the mound did not appreciably change shape between July, 2001 and July, 2002 (Fig. III-2). Image comparisons revealed a slight overall increase in size and an increase in the number and size of exposed gas hydrate-filled crevices on the flanks and margins of the mound (Fig. III-3). The mound had an irregular shape about 2.5m across and roughly 65cm of relief. The eastern edge of the mound was buried in sediment, and the southern edge was undercut with a small overhanging ledge. The sediment cap on top of the mound varied in thickness over the time-series, and was constantly redistributed by water movement at the site. The cap was scoured away in some places exposing gas hydrate to the water while new sediment covered up exposed patches. Overall, the sediment layer appeared to substantially thin over the year of observations.

Despite the lack of gas expulsion from the gas hydrate outcrop itself, a bubble plume on the western side of the mound, less than a meter away but outside the time-lapse camera's field of view, has been releasing natural gas and oil almost constantly for several years. This area is a part of the gas hydrate mound since the base of the plume is surrounded by gas hydrate (Fig. III-4) and the outcrop extends for some distance below the sediment on all sides. There is no obvious crevice or fault from which the oil and gas escape. They appear to issue directly from the gas hydrate, which is evidently a more permeable portion of the deposit. The constant presence of the bubble plume illustrates the active nature of seeps, and while the gas may not be the result of gas hydrate dissociation, it does affect the formation's longevity.

Discussion

Bush Hill has been a focus of study since the discovery of Gulf of Mexico cold seep communities in the 1980s (Kennicutt II 1985). The chemosynthetic ecosystems found at this site and similar cold seeps in the Gulf of Mexico are intimately associated with hydrocarbon seepage. Some portion of the gas is trapped by gas hydrate formation at or near the sediment/water interface. The irregular crevices that undercut the mounds, and the distribution of sediment on and around them, support the theory that

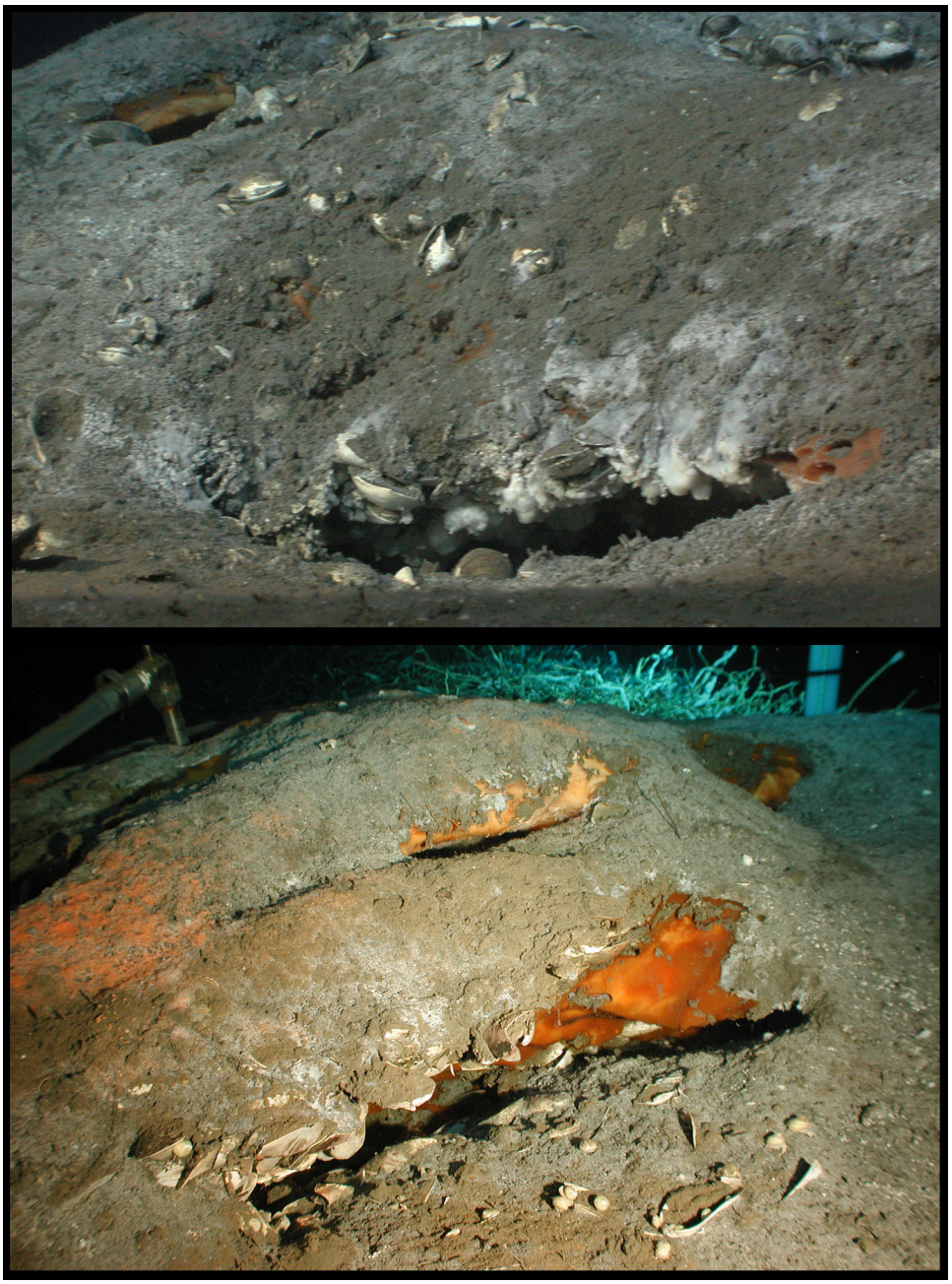

Fig. III-3. These high resolution pictures illustrate the extent and depth of the crevices that opened in the face of the gas hydrate outcrop over the deployment period. They were taken by a SeaSnap 990 camera attached to the Johnson Sea Link submersible. The top photograph, taken in 2001 shows the undercut area at the base of the mound (the rounded burrows in the orange exposed gas hydrate on the right are possibly due to biological activity), and a small crevice higher up on the left side of the mound. The bottom photograph, taken a year later, shows the same crevices from a different angle. Some of the sediment cover was removed by submersible activity at the site, exposing more gas hydrate, but the increased undercutting and deepness of the fissures is evident.

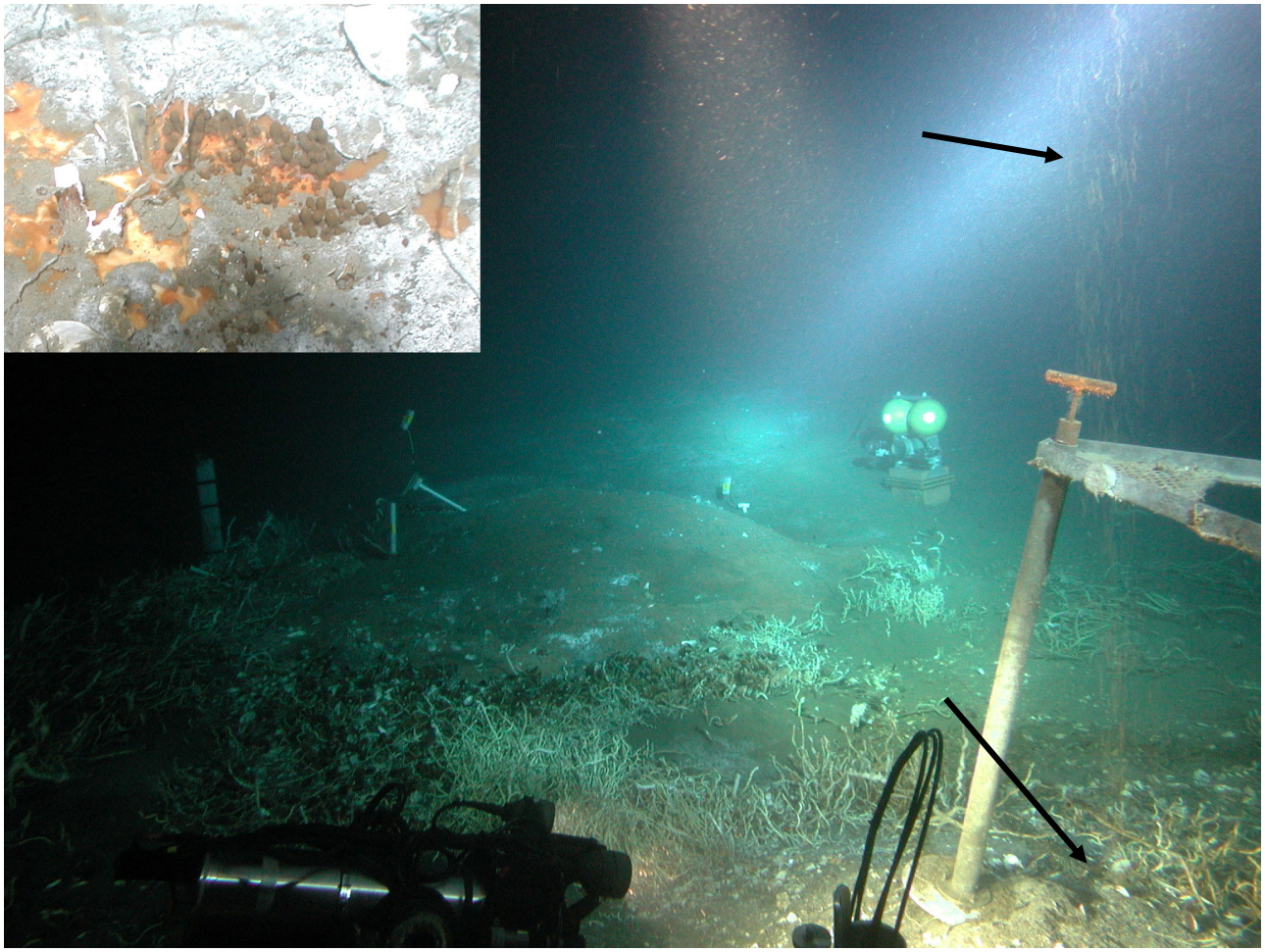

Fig. III-4. This picture shows the gas hydrate outcrop and time-lapse camera at center and the nearby bubble plume on the far right (arrows). The inset picture, taken in the area indicated by the lower arrow, shows oil droplets (brown spheres) issuing directly from the gas hydrate (orange) and about to break away and float into the water column from the base of the bubble plume. Both pictures were taken by a SeaSnap 990 camera attached to the Johnson Sea Link

outcroppings form beneath the sediment and push upwards as they increase in size. The mound retains some of the sediment in the form of a thin "cap" that drapes over the gas hydrate (MacDonald, et al. 1994). As the mound is pushed up from beneath by further gas hydrate formation it begins to crack and is undercut by exposure to seawater. Bacterial mats are ubiquitous at cold seeps (Nikolaus, et al. 2003) and may be uplifted as the gas hydrate mound grows. Alternatively, they may grow on top of the sediment cap after the outcrop breaches the seafloor.

Insulation by sediment and bacterial mats may delay gas hydrate disassociation, but it does not indefinitely preserve the mound. The sediment cap gradually thins as water currents erode the surface and the weight of the sediment counteracts the buoyant nature of the gas hydrate. Bacterial oxidation of methane, which is responsible for the massive carbonate deposits found at many seep sites, may accelerate the dissociation process. As the mound is increasingly undercut and the sediment layer thins, the outcrop may break free and float intact into the water column (Suess, et al. 1999; Paull, et al. 2003). Gas hydrate that is exposed to the water column is destabilized by temperatures that exceed gas hydrate stability. Bottom water temperature seasonally fluctuates by 6-11 °C with a mean temperature of 7 °C. A structure II gas hydrate outcrop may change in shape, and even completely disappear, in periods of less than a year (MacDonald, et al. 1994). In previous studies the undercutting of the gas hydrate has been primarily attributed to temperature changes at the site, since pressure is relatively constant at these sites absent major geologic activity or seafloor slumping (Xu and Lowell 2001). The lack of change in the shape or size of the gas hydrate outcrop observed in this study, despite temperatures that exceeded the threshold necessary for dissociation by nearly 1°C, indicates a greater stability than previously described in laboratory studies and prior *in situ* observations.

While active bubble plumes increase flow during up spikes in bottom water temperature (MacDonald, et al. 1994), persistent gas hydrate outcroppings are apparently more inert, possibly due to the high concentrations of oil and sediment that are trapped within the structure of the mound (Waite, et al. 2002). Over the ~1-year time scale of observation, this particular gas hydrate deposit was stable. This stability indicates that the seep environment provides a stable settlement and colonization area for

chemosynthetic as well as benthic colonizing species. It also has implications for the future exploitation of this habitat by oil companies and the possible use of hydrate as an alternative energy source (Milkov and Sassen 2002). If gas hydrate is not as volatile as previously thought then destabilization and slumping do not present as great a hazard to deep-sea development and drilling and gas hydrate deposits may be persistent enough to be mined and produced as a fuel.

CHAPTER IV

BIOLOGICAL ACTIVITY

Introduction

Although little topographic change was observed in the gas hydrate mound, the time-lapse camera captured a number of biological processes. The time-series of photographs provided enough data for a population survey of seep organisms, including the abundance and behavior of the species that appeared and their interactions with the gas hydrate substrate. It was theorized that a major seafloor feature such as the gas hydrate mound would be an aggregation point for numerous predatory species because it provides shelter and an energy source for benthic seep organisms.

Results

The number and type of organisms observed on or around the hydrate outcrop were identified in the series of time-lapse still images. Each image was individually scrutinized and compared to the previous and following images to identify any organisms present and other biological activities that occurred during that frame. Individual organisms were counted, preliminarily identified, and tallied to provide the number of organisms per image. Distinct behavior patterns or unusual events in an image were noted as well. The pictures recovered from the first long-term deployment had a resolution of 1,024 x 756 pixels, which is generally detailed enough to identify the genus of large macrofauna and megafauna, but not sufficient to positively identify some of the smaller organisms. The short-term record had a higher resolution of 2048 x 1536 pixels, which allowed even greater accuracy in identifications. The digital camera's lens aperture was locked at 7.0 for both deployments, which allowed for maximum depth of focus over the entire field of view but did cause motion blurring if an organism was overly active at the instant a picture was taken. Positive identification to the species level usually requires capture and

Table IV-1.
Seep organisms observed during deployment period

Species	First Deployment	Second Deployment	Overall	Behavior
Munidopsis n. sp. (Squat lobster)	118	236	354	Colonized all foreign objects. Scavenged all areas of mound and crevices.
Munida sp. (Squat lobster)	1	0	1	Vagrant predator. Seen on top of camera lens for a single frame.
Rochinia crassa (Spider crab)	11	9	20	Vagrant predator. Wandered around outcropping area.
Chaceon quinquidens (crab)	4	2	6	Vagrant predator. Wandered around outcropping area.
Trichopeltarion nobile (crab)	4	16	20	Vagrant predator. Wandered around outcropping area.
Sympagurus pictus (Hermit crab)	3	0	3	Vagrant predatory species with sea anemone that grows on shell.
Zoroaster fulgens (?) (starfish)	25	3	28	Large sea star that wandered around the base of the outcropping.
Valvatida starfish	58	0	58	Climbed up and down mound, disturbing sediment and bacterial mats.
Buccinid snail	34	0	34	Only individual seen laid eggs on top of thermistor probe.
Hoplostethus sp. (Orange Roughy)	286	502	788	Difficult to count accurately - moved in large schools and almost constantly present
Bembrops sp. (Duckbill Flathead)	15	7	22	Vagrant predator. Wandered around outcropping area.
Helicolenus dactylopterus (?)	3	5	8	Vagrant predator. Occasionally rested on or below outcropping.
Synophobranchus sp. (eel)	2	4	6	Swam around outcropping. Able to enter small crevices in mound for shelter and/or predatory behavior.
Urophycis cirratus (hake)	1	2	3	Vagrant predator. Wandered around outcropping area.
Macrourid sp. (Rattail)	3	0	3	Vagrant predator. Wandered around outcropping area.
Chaunax sp. (Gapers)	3	3	6	Vagrant predator. Occasionally rested on or below outcropping.
Unidentified Organisms	13	7	20	Organisms that were either blurred or too far away to positively identify.
Total	**584**	**796**	**1380**	

detailed anatomical analysis of a specimen, but some organisms in the record were tentatively assigned to a species based on previous studies at seep communities.

During the long-term deployment a total of 590 individual organisms were observed, at an average of 3.1 (±2.7) per frame. A total of 796 individuals were counted during the short-term deployment with an average of 3.1 (±4.1) per frame. At least 16 distinct species were seen, as well as a number of unidentifiable organisms that were either too far from the camera or too blurry to categorize. These results are summarized in Table IV-1. Two varieties of *Beggiatoa* bacteria, which formed large colonial mats over much of the sediment and gas hydrate outcrops, were present during the entire deployment periods.

Bacteria

Beggiatoa bacteria are an ubiquitous presence at hydrocarbon seeps around the world (Nikolaus, et al. 2003). These filamentous colonial organisms mainly metabolize H_2S that is found in abundance in the sediments and bottom water at seep sites. Two morphological types coexist at the Bush Hill site, but show competitive exclusion within their colonial patches, with only slight intermingling at the edges of adjoining bacterial mats (Fig. IV-1). One type lacks pigment, and forms thick, dense mats around areas of high sulfide flux. These bacterial mats also contain a vibrioid species of *Arcobacter*, which produce a white flocculent material that builds up into drifts that are subsequently dispersed by currents or biological activity (Wirsen, et al. 2002). The white substance may be elemental sulfur extruded in response to sulfide that is being delivered at rates beyond the bacterial capacity to metabolize. The other type of *Beggiatoa* is orange in pigmentation and is apparently facultatively heterotrophic (Nikolaus, et al. 2003). Nikolaus et al. have found that the orange bacteria do not incorporate CO_2 as well as the white bacteria and have a lower rate of RuBisCO activity. The orange *Beggiatoa* are also able to metabolize compounds other than sulfide. The extent and thickness of the bacterial mats around the gas hydrate outcrop waxed and waned during the time-lapse camera deployment period. Only white *Beggiatoa* mats were observed growing on the mound during the longer deployment period, although orange bacterial mats could be seen in the area

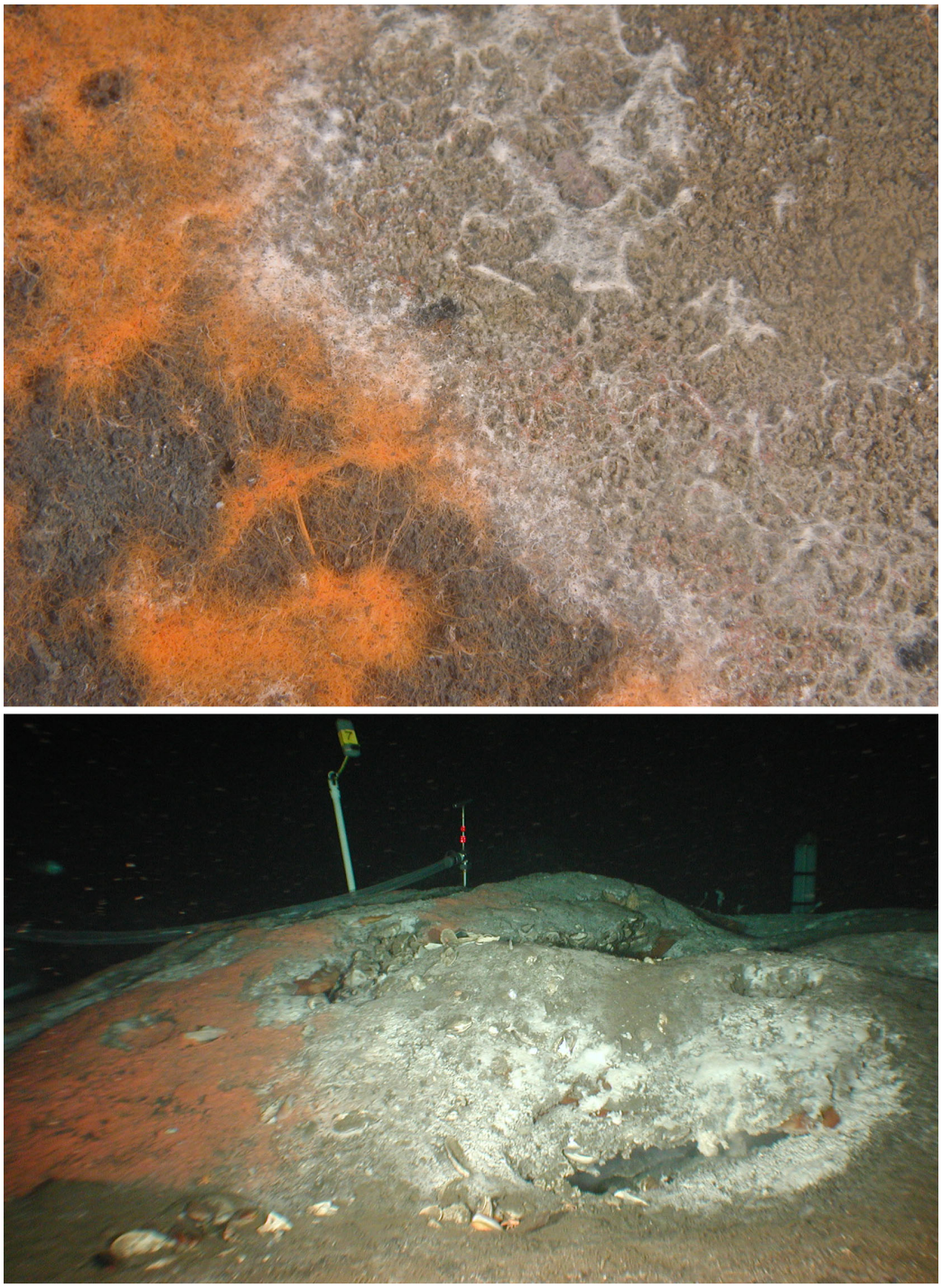

Fig. IV-1. Orange and white *Beggiatoa* bacteria show competitive exclusion (top) and were both found growing in colonial mats on top of and around the gas hydrate outcropping under investigation (bottom). Some of the flocculent material extruded by a different species (a vibrioid *Arcobacter*) that grew in the white mats can be seen in the center of the mound and above the undercut region on the bottom right.

around the site. Bacteria covered almost the entire area of the gas hydrate mound at certain times. The white bacteria showed no apparent response to temperature, sediment resuspension or time of day. The mat was occasionally scoured by currents or biological activity that scraped entire patches or trails down to the bare sediment. These areas would then fill with new bacterial growth within 24 hours. It was not possible to determine whether the bacteria were being grazed or simply brushed aside by the benthic fauna at the site. Flocculent sulfur extruded by the vibrioid bacteria in as little as six hours (the interval between images during the longer deployment) often built up in feathery drifts 3-4 centimeters high on top of the mound and overhanging the prominent undercut area below the southern face of the mound. This continued for several days until the material was either swept away by bottom currents or disturbed by organisms, and then the cycle began again.

Approximately one third of the upper surface of the gas hydrate outcrop was colonized by orange *Beggiatoa* between the first and second deployment periods. The area of orange bacterial cover may also have been more visible due to the slightly greater northward orientation angle of the time-lapse camera during the second deployment, relative to the camera position during the first deployment (see Methods section). The distribution of white bacteria on the central and eastern side of the mound was similar to that exhibited during the first time-series. The higher resolution images and shorter time-lapse interval allowed for closer observations of bacterial growth rate and the speed of flocculent production. Trails and areas cleared of white bacteria had invariably recovered in 22-24 hours, as before. However, it became evident that a significant quantity of flocculent material could build into drifts 1-2cm high in as little as 2 hours and be removed anywhere from 18 hours to several days after first becoming visible on top of the white bacterial mat. The orange *Beggiatoa* mats grew on the western third of the mound (Fig. IV-2), extending slightly farther east on the side of the mound farthest from the camera, and exhibited slightly different growth patterns than the white mats. No flocculent material was extruded from these bacterial mats during the deployment period. The mat varied from thick and bright orange to sparse and almost imperceptible during the 1 month time-series, often waxing and waning within 2 hours. The cycles of waxing and waning were often separated by long periods of days to weeks when no change was observed other than biological or current-related disturbance. Although several attempts were made to quantify the

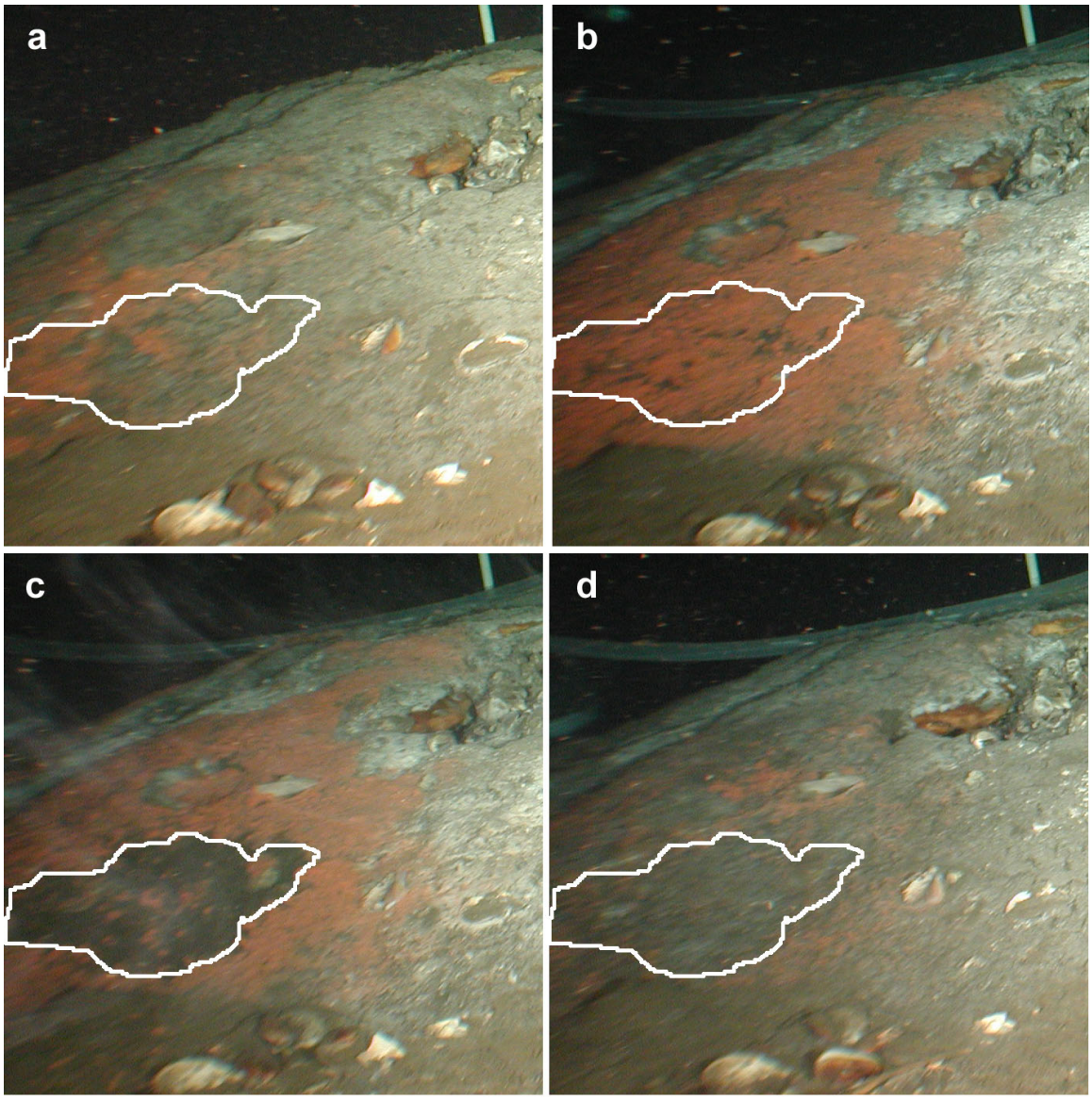

Fig. IV-2. The portion of the gas hydrate outcropping covered by orange *Beggiatoa* bacteria. The mat coverage could increase from sparse (a) to thick (b) over periods of 2 hours to several days. One section was apparently scoured clean by a burst of strong water movement on 18 June 2002 (c) and had not completely grown back by the end of the record on 3 July 2002 (d). The outline of this area is illustrated by the white line in all four images. The general lack of bacterial cover visible in the final image is partially due to a natural waning cycle, but was even more distinct within the outlined area.

amount of bacterial coverage over time, there was no discernable pattern to this behavior. The increasing and decreasing visibility of the orange bacterial mat may involve movement of individual bacterial filaments into and out of the sediment cap covering the gas hydrate rather than growth and recession of the mat itself. Similar behavior has been observed in this species during previous studies, although not within such short time intervals (Sassen, et al. 1993c; Nikolaus, et al. 2003). Most biological and physical disturbance of the orange mat was overgrown within 24 hours, as with the white bacteria. However, a large area of orange bacterial mat was apparently scoured bare by a turbulent bottom current on 18 June, 2002 at 2:56 PM and was still visibly lacking in bacterial growth by the end of the time-lapse record on 3 July, 2002.

Invertebrates

The invertebrate organism that most typifies the Bush Hill gas hydrate community is the tubeworm, which grows in large, tangled aggregations that resemble bushes and cover large areas around the site. However, aside from a few empty tubes embedded in the sediment covering the mound, the camera's field of view encompassed only a single aggregate of tubeworms. That colony was in the far background, out of focus, and often obscured by suspended sediment. The number of individual worms, their species or their behavior could not be distinguished based solely on analysis of still images. Therefore they are not included in organism inventories. Other species of polychaete worms can also be found at Bush Hill, such as *Hesiocaeca methanicola*, which colonize gas hydrate mounds at this and other hydrocarbon seep sites in the Gulf of Mexico. No clear evidence of the presence of these worms was observed in the record. Periodic biological activity was observed within an undercut area on the southern face of the mound, and it was theorized that this could be evidence of a colony of *H. methanicola*. However, the image resolution was insufficient to determine if the organisms were Alvinocarid shrimp, which have the same pinkish coloration and are also commonly found in crevices around gas hydrate outcrops. No organisms were collected from the area under the mound during suction sampling.

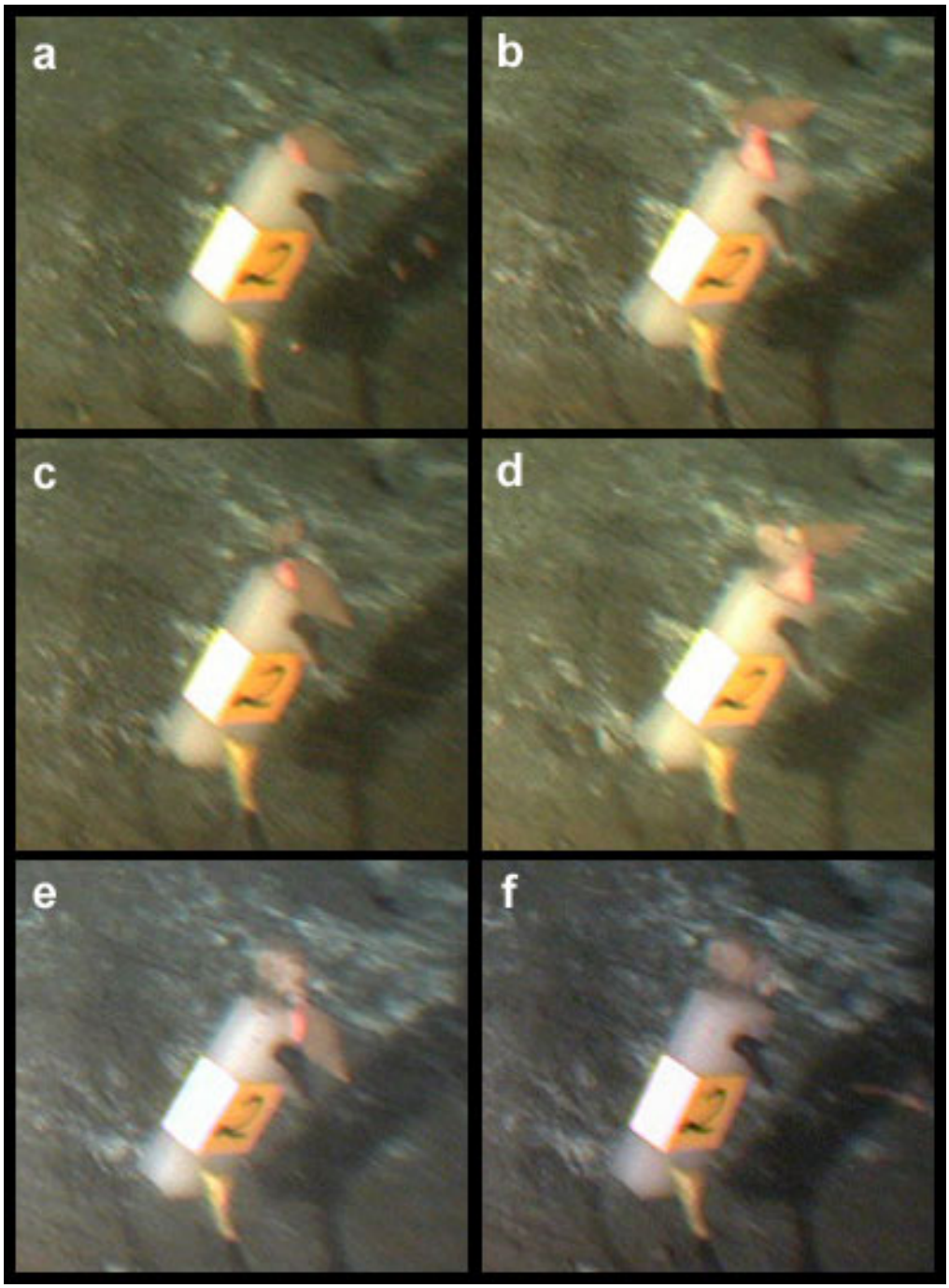

Fig. IV-3. This series of images (cropped and enlarged to show detail) captured a Buccinid gastropod laying a number of eggs on top of a marker float attached to one of the temperature probes. The snail first appeared at 18:00 on 9 October, 2001 (a) and had begun laying eggs within six hours. This egg-laying behavior (b through e) continued until 18:00 on 18 October, after which the individual was not visible again in the record. The time-lapse record ended less than a day later, so survival rate and hatching of the eggs could not be determined. The eggs were not present when the temperature probe was recovered in 2002.

An unknown species of coldwater whelk from the order Buccinidae was occasionally seen in the record, but either so far away from the camera lens that it was impossible to identify or off to one side of the field of view and blurred. All gastropods seen in the record had a brown shell and red-orange body. Over a period of nine days late in the record, one individual laid a number of eggs on top of the float attached to one of the thermistor probes deployed next to the camera (Fig. IV-3). This egg-laying behavior, consisting of periodic lifting of the shell, attaching an egg, lowering the shell and repeating, is seen in the Gulf of Mexico only in snails of the order Buccinidae (M. Wicksten, personal communication). The first time-lapse deployment ended less than 24 hours after the eggs were laid, so neither the survival rates nor the time between egg production and hatching could be determined. No eggs or evidence of their presence were evident when the temperature probe was recovered the next year. Despite their low representation in the photographic time- series, the existence of large numbers of these snails was indicated by the number and frequency of bare sediment trails they left through the bacterial mats on top of the gas hydrate mound.

The most frequently sighted invertebrate in the time-lapse record was a small galatheid crustacean, an as yet undescribed species of *Munidopsis* (Fig. IV-4). These decapods range in size from less than a centimeter to 10cm in length. They have a bright orange coloration, a squat body, and short appendages except for an elongated set of front claws which can be over twice the length of the rest of the body and are used to feed. During both deployment periods, galatheids could be seen wandering over the entire surface of the mound and the sediment surrounding it. They seemed especially attracted to foreign objects and areas of elevation, often fighting over the space at the top of thermistor probes and the scale markers left at the site. They also left trails in the bacterial mats covering the mound. 354 galatheids were counted in the images during both deployments of the camera; however their generic appearance, colonial behavior and sluggish movements caused the same individuals to be counted several times, making it difficult to determine the true size of the population.

Fig. IV-4. Crustaceans observed at the gas hydrate mound (not to scale). Clockwise, from top left, they are *Chaceon quinquidens*, two different angles of *Sympagurus pictus*, *Trichopeltarion nobile*, *Rochinia crassa*, *Munida forceps*, and *Munidopsis* unk. sp. The picture of the *Munidopsis* is from a high resolution SeaSnap 990 attached to the Johnson Sea Link submersible because the small size of the organism and the lower resolution of the time-lapse images made these galatheids difficult to see clearly when enlarged.

The other crustaceans observed at the site were seen intermittently and only remained in the area for short periods of time (Fig. IV-4). The largest of these were of the species *Rochinia crassa*, also known as spider crabs. These red and white crabs were seen in a wide range of sizes, with the smallest being about 20cm across and the largest measuring 60-70cm. Based on its size and the shape of its pincers, the largest individual was probably an adult male (M. Wicksten, personal communication). These crabs moved relatively quickly, usually spending less than 2 hours at the site and therefore only visible in a single frame of the time-lapse record. A second type of decapod lobster was also observed at the site. Probably *Munida forceps*, this species is larger than the *Munidopsis* species, has a darker red coloration and is able to swim. One individual spent some time on the lens of the time-lapse camera, possibly indicating an attraction to foreign objects similar to that seen in the smaller galatheids. Crabs of species *Chaceon quinquidens*, which was formerly placed in the genus *Geryon*, were seen intermittently at the site. *C. quinquidens* has a flattened, trapezoidal, angular shaped carapace and brownish-white body, with thin, bright red legs. Several smaller, brown crabs, probably *Trichopeltarion nobile*, also occasionally scavenged around the gas hydrate mound area. This species is uniformly brownish-grey in coloration, with a round body and some sort of fibrous material on the shell and appendages, possibly due to bacterial growth or a natural defensive trait. Finally, three hermit crabs of species *Sympagurus pictus* were seen during the first deployment. These hermit crabs have an unusual distinguishing characteristic: they carry sea anemones on their shells for protection and camouflage, the only species of crustacean in the Gulf of Mexico to exhibit this behavior.

Two separate species of echinoderms were observed in the area around the gas hydrate outcrop on multiple occasions (Fig. IV-5). The first was a large starfish, probably *Zoroaster fulgens*, which was occasionally seen around the base of the mound. This species is very common in the Gulf of Mexico and can be found at water depths of 300 to 3000 meters (A. Ammons, personal communication). The individuals seen in the record were approximately 20 to 25cm across, had a beige or orange coloration, short spines on the dorsal surface, and long arms connected to a small central body. While no specific feeding behavior was observed, the starfish did move around the base of the mound examining mussel shells and other detritus that had accumulated. The individuals observed would generally remain at the

Fig. IV-5. Asteroids observed at the outcropping. Pictured are two *Zoroaster fulgens,* at left, and three shots of one Valvatid starfish that moved up and down the mound for almost a month in 2001.

site for 6 to 12 hours before moving on, although occasionally one would only appear in a single frame before leaving.

The second species of starfish was smaller and white in coloration, with short, rounded arms and a proportionally larger body. It remained at a distance of about a meter from the camera lens, which was too far for positive identification. Based on its superficial appearance it was probably a member of the order Valvatida, which contains over 100 species in the Gulf of Mexico (A. Ammons, personal communication). Although this species appeared in 58 frames during the first deployment, the movements, size and appearance of the individual indicates that all of these sightings were of one starfish. It moved up and down the southern face of the outcropping several times, pausing to enter crevices and move around the base of the mound as well. These movements disturbed the bacterial mats and occasionally rearranged several empty mussel shells and dead tube worms that had settled around the mound. Including certain time-lapse shots in which the starfish was present but not visible because it was concealed in a crevice on the mound, this starfish remained on and around the gas hydrate mound for at least 29 days.

Vertebrates

The time-lapse camera revealed several species of fish that inhabit the gas hydrate mound area and the area of the water column directly above it. Surprisingly, the most common organism seen in the entire record was a fish rather than a benthic invertebrate. Individuals of the genus *Hoplostethus* (also known as deep-sea perch or orange roughy) were seen swimming back and forth over the outcropping in nearly every frame of the time-lapse record, but they most commonly appeared as members of large schools of 20 or more (Fig. IV-6). *Hoplostethus* species are silver in color, but often appeared red or white in the light from the camera array. They have extremely horizontally flattened bodies, large eyes, crescent-shaped tail fins and small dorsal and pectoral fins. Individuals ranged from 10 to 30cm in length. The coloration, thin profile and tendency to appear in tight clusters made it difficult to get an accurate count, but approximately 800 of these fish were seen during both time-lapse records. Nearly twice as

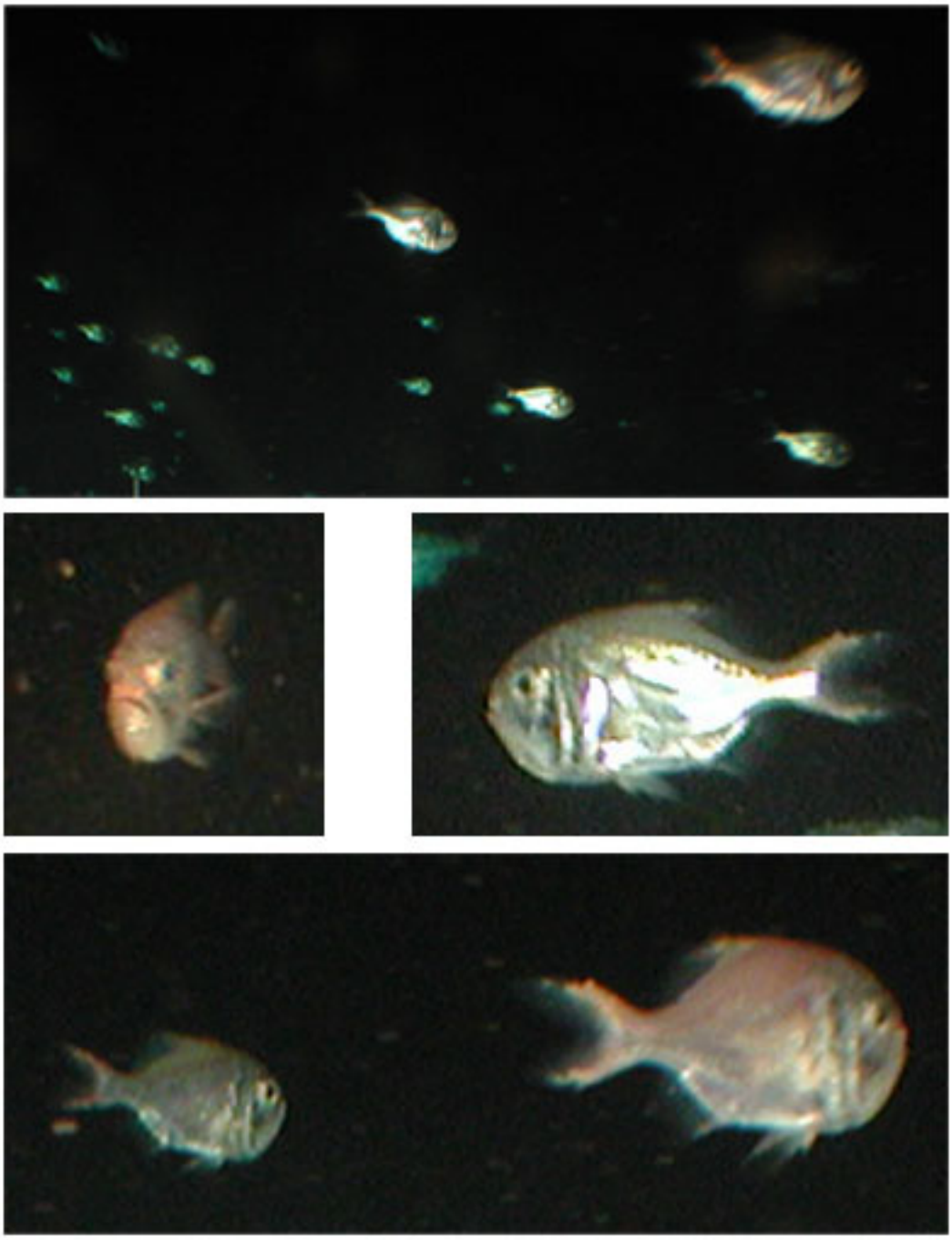

Fig. IV-6. Examples of *Hoplostethus* sp. seen in the time-lapse record. The image at top illustrates the average size of the schools that these fish generally traveled in. The middle two images provide head-on and profile shots of this species, while the bottom image shows the range in apparent coloration depending on distance and angle with respect to the camera lights.

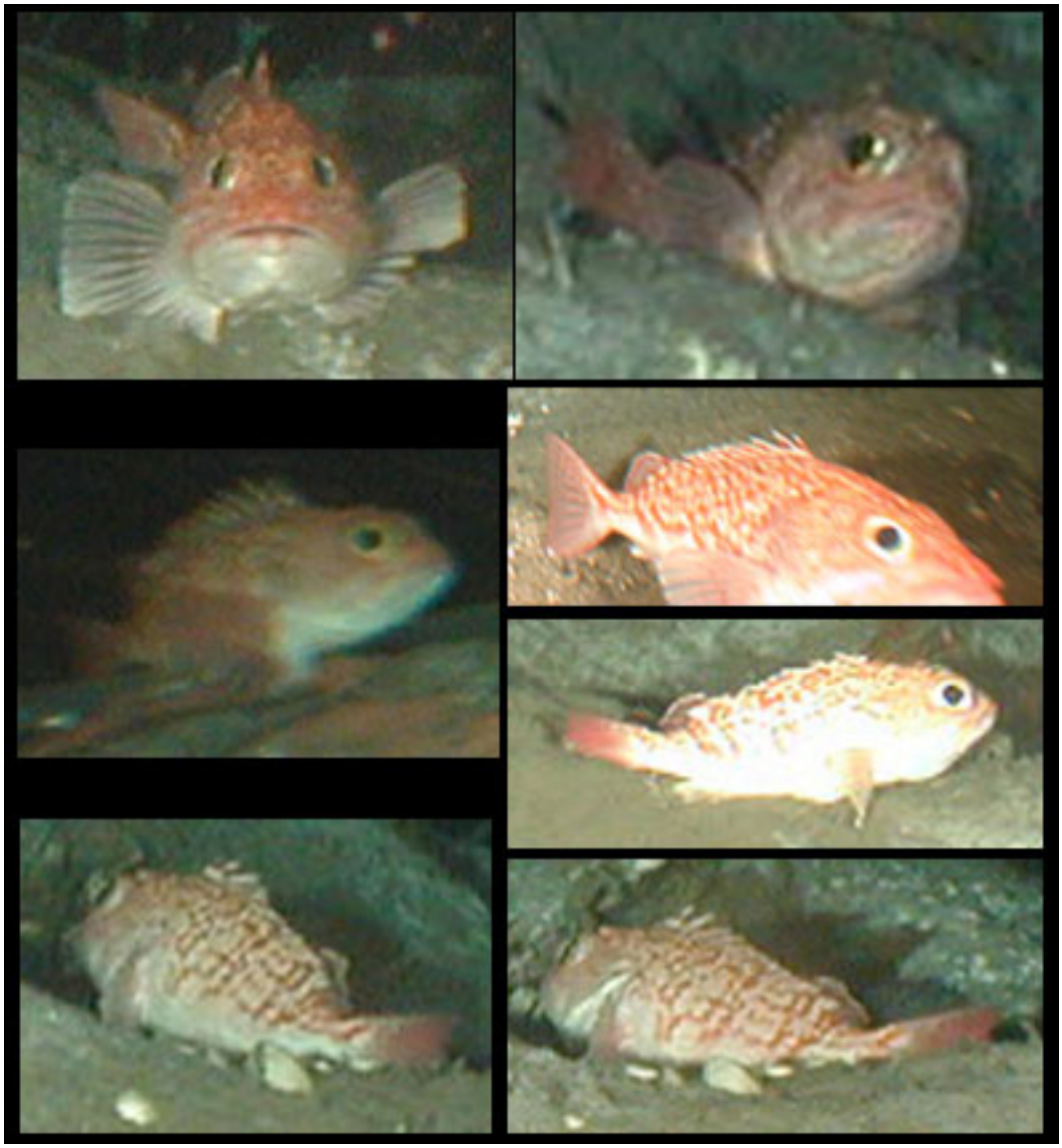

Fig. IV-7. Facing, profile and rear-angle shots of *Helicolenus dactylopterus* (Black-belly rosefish) individuals seen around the gas hydrate mound during the deployment period.

many *Hoplostethus* were seen during the second, one-month record than during the first, three-month record (500 vs. 280).

The other fish that appeared in the time-lapse record were seen rarely and for short periods of time, which is indicative of vagrant predator species. *Helicolenus dactylyopterus* (also known as the black-belly rosefish), a well-described species known to inhabit the deep Gulf of Mexico (J. McEachran, personal communication), hovered above and rested on the mound at different times during the deployment period (Fig. IV-7). These orange and white fish wait in a location for prey to approach them, making the relatively high biological activity around the hydrate mound an ideal hunting ground. *Chaunacids*, or gapers, are another species of sessile predator that frequent the area around the gas hydrate outcropping (IV-8). Bright red-orange in color, these fish have a disproportionately large head and mouth, with strong, fleshy pectoral fins that it can use to move over the bottom and a small, tapering tail. A more active predator is *Urophycis cirratus*, a deep-sea hake. These long, grey fish have large eyes, a tapering body and sensitive feelers on the sides of their bodies anterior of their pectoral fins. Similar to the whiskers of a catfish, *Urophycis* species use their feelers to hunt for animals hidden in the upper layers of the sediment. This fish is a common sight at seep locations throughout the Gulf of Mexico, but was only seen in the record a few times, usually at some distance from the camera lens. *Macrourids* have a similar body shape to *Urophycis*, but have no feelers, a long, triangular dorsal fin and a tail that tapers to a point. Three of these "rattails" were seen during the first deployment. A species of fish from the genus *Bembrops*, small and iridescent green and silver in color, was seen hovering around the mound during both deployments. These benthic predators have elongated bodies and thin heads with protruding lower jaws, which gives them the common name of duckbill flatheads. *Synophobranchus* eels were occasionally seen entering and exiting crevices around the base and flanks of the mound (Fig. IV-9). This species of eel is very thin, ~5 cm wide and 40 to 50 cm in length and a uniform dark grey in coloration.

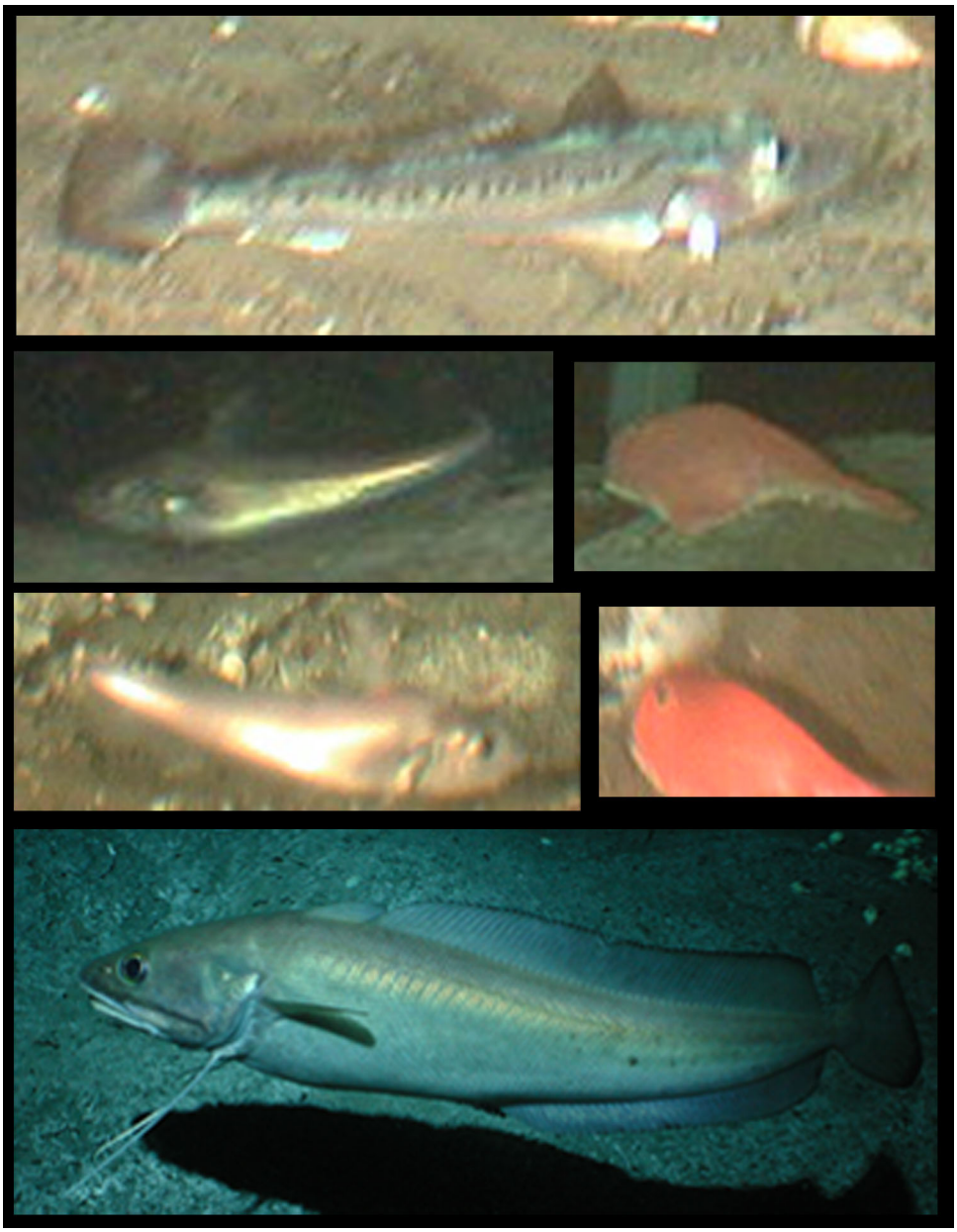

Fig. IV-8. Some of the vagrant predatory fish seen at the gas hydrate outcrop. Clockwise, from top, they are *Bembrops* sp., two different Chaunacids (or gapers), a *Urophycis cirratus*, and two Macrourids (or rattails). The bottom picture is from a high resolution SeaSnap 990 attached to the Johnson Sea Link submersible. All other images were taken by the time-lapse camera.

Fig. IV-9. Eels of genus *Synophobranchus* could be seen swimming over and within crevices of the gas hydrate mound.

Discussion

The amount of biological activity captured by the time-lapse camera seems to indicate that the gas hydrate outcrop is a major feature of the benthos. The high level of bacterial activity provides evidence of the chemosynthetic potential of the gas hydrate and serves as the base of the seep food chain. Although there were very few obligate seep organisms seen in the record, several species of known seep colonists appear to inhabit gas hydrate mounds and forage in the general area. The importance of massive gas hydrate to the seep community is also shown by the number of vagrant predators and highly mobile species seen in the vicinity of the outcrop. In addition, the effect of biological interactions on the gas hydrate mound is evident from the excavation and colonization of naturally occurring crevices and fissures on the flanks and base of the outcrop. These features provide shelter for smaller organisms, as well as areas of exposed gas hydrate that provide a substrate for bacteria and burrowing polychaetes.

The two types of *Beggiatoa* bacteria and the *Arcobacter* species that coexist on and around the gas hydrate outcrop may help anchor the sediment cap that covers the gas hydrate and insulate it from the bottom water. Cycles of growth and retreat, while not apparently connected to any of the physical properties recorded by the remote sensor array, imply that these bacterial colonies are sensitive to and affected by changes in the environment. For example, they may be responding to changes in the episodic release of sulfide at the site, or other chemicals released by the seep. Production of flocculent material by the *Arcobacter* species of bacteria implies a chemical influence as well. The topography of the mound may also affect current directions and velocities, aiding in bacterial dispersal and colonization of the wider seep area.

Although seldom seen in the time-series, Buccinid snails represent important bacterial grazers in the seep food chain. By clearing areas of bacterial cover they expose sediment substrate for new colonization, and may loosen the sediment cover of the gas hydrate mound. They apparently use hard substrate and elevated topography to reproduce, evidenced by the appropriation of the temperature probe as an anchor for egg cases. While they may not use solid gas hydrate for this purpose, the bacterial

activity and detritus that are concentrated by the outcrop's topography make gas hydrate a significant feature in the life cycle of these gastropods.

High numbers of crustaceans were seen in the time-lapse record, which was mostly due to the presence of one species of *Munidopsis* and the relatively slow speed of movement of the others. The multiple sightings of *Sympagurus pictus* hermit crabs were somewhat unexpected, as this species has been very rarely observed in previous biological surveys of the Gulf of Mexico. While most of the crustaceans that appeared in the time-series were vagrant predators, such as *Rochinia crassa*, and *Chaceon quinquidens*, based on this record and previous site surveys the *Munidopsis* species that was seen is apparently a seep colonist. They are not directly dependent on chemical seep production, but probably obtain most of their food from the obligate seep species and detritus that are found around the gas hydrate mound area. The trophic differences between the invertebrate species found at seep sites have been confirmed by stable isotope analysis in previous studies (MacAvoy, et al. 2002). The numbers of *Munidopsis* spp. that appear in the photographs, and the speed with which they incorporated foreign objects such as the temperature probes into their territory, indicates a relatively high density population and elevated levels of competition for space and resources at the seep site.

The two species of starfish that were observed around the gas hydrate mound exhibited slightly different behaviors. *Z. fulgens*, the larger species, was seen multiple times in the record for short intervals and is probably a vagrant predator that is attracted to the gas hydrate outcrop by the elevated quantity of food sources as compared to the background benthic community. The smaller Valvatid species was only seen once during both deployment periods, but remained in view of the camera for almost a month. This behavior pattern seems to indicate that this starfish species is a seep colonist: not entirely dependent on the seep for food, but subsisting on seep organisms as a large part of its diet. However, given that this species was not seen again in the records after this one extended period, it could be a vagrant predator that simply paused at the seep site for a time.

One of the most unexpected findings of the species survey was the large number of *Hoplostethus* that were seen. Equally surprising were the greater numbers seen during the one-month camera deployment than during the three-month deployment. This could be a random statistic or an artifact of

greater rates of identification due to the higher resolution of the pictures taken during the one-month record. Alternatively, it could be a true representation of a population or territorial change at that time of year (June to July as opposed to July to October), or a pattern of activity made evident by the shorter time-lapse interval during the second deployment (2 hours vs. 6 hours). In either case, the density of these organisms at the site and their nearly constant presence over the entire record could indicate that they are a seep colonist species. They would most likely derive a great deal of their nutrition from bacteria, microfauna and larval seep species that are suspended in the water column over the seep site. Although little is known about the behavior of Gulf of Mexico *Hoplostethus* species, certain Atlantic and Pacific species are known to aggregate around topographic rises and seamounts (J. McEachran, personal communication). The raised topography of the Bush Hill mound could explain the concentration of this species at the seep site. However, it is possible that the large numbers of *Hoplostethus* seen at the site were artificially inflated by attraction to the illumination provided by the time-lapse camera array or prey that may have been drawn to the lights. This would also explain the greater numbers during the one-month record, since the lights were on three times more frequently during that deployment. Since the behavior of this species in response to long-term exposure to light sources is unknown, no definitive conclusions about the natural population of this species at the site can be drawn.

The other fish species that appeared in the time-lapse photographs were rarely seen and probably vagrant predators. One of the most common fish seen at the Bush Hill site during submersible operations, *Urophycis cirratus*, was only seen 3 times in the entire deployment period. The discrepancy between their ubiquity during submersible dives and scarcity in the time-lapse record may be explained by their spatial heterogeneity, mobile hunting patterns and relatively rapid movements, or it could be an indication that this species was avoiding the deployment area, perhaps disturbed by the lights or electronic activity. The *Synophobranchus* eels were often observed entering or leaving crevices in the gas hydrate outcrop, a unique ability among the predatory fish species. Their elongated bodies allow them access to fissures and areas of the mound that other fish would be unable to reach, making the gas hydrate mound a niche hunting ground and protective shelter for the eels. Their numbers may also be greater than indicated, as they could escape notice while inside a crevice.

The large number and relatively high diversity of organisms observed at the mound absent any bait or other artificial inducement indicates that gas hydrate outcrops provide a relatively stable environment and possible food source for deep-sea organisms. Previous results indicate that many benthic predators derive significant nutrient carbon from seeps (MacAvoy, et al. 2002). Gas hydrate deposits are a focus for biological activity.

CHAPTER V

SEDIMENT RESUSPENSION

Introduction

One particularly noteworthy physical process captured by time-series observation was the extensive amount of sediment resuspension and redistribution that occurred during the deployment period. The current strength and velocities powerful enough to lift sediment and detritus into the water column indicate greater disturbance and water movement than expected at these depths. Previous studies utilizing current meters have also not observed current speeds that would indicate such activity. The amounts of sediment resuspension that were seen in the time-lapse record will have a considerable impact on the geology and biology of the gas hydrate mound.

Results

Significant levels of sediment resuspension were observed in both sets of time-lapse images, at times obscuring the entire frame, indicating a number of turbulent events (Fig. V-1). While no equipment present was capable of determining the exact concentration of particulate matter suspended in the water column, the amount of sediment present in each picture could be quantified by using ImageJ® image-processing software developed by the National Institute of Health. The visible portion of the water column above the mound was highlighted in each frame, with equipment and other persistent objects excluded. A corresponding histogram was then created, measuring the luminosity of the highlighted portion on an arbitrary scale from zero light penetration to entirely transparent. Higher luminosity indicates greater amounts of turbidity, and thus greater amounts of suspended material, while low luminosity indicates less turbidity. The luminosity data for each image was then plotted on a time scale and analyzed for periodicity using Matlab software (Fig. V-2). Similar analysis was performed on the temperature data. The temperature record exhibited peaks at a 23.9 h (K1) period during both

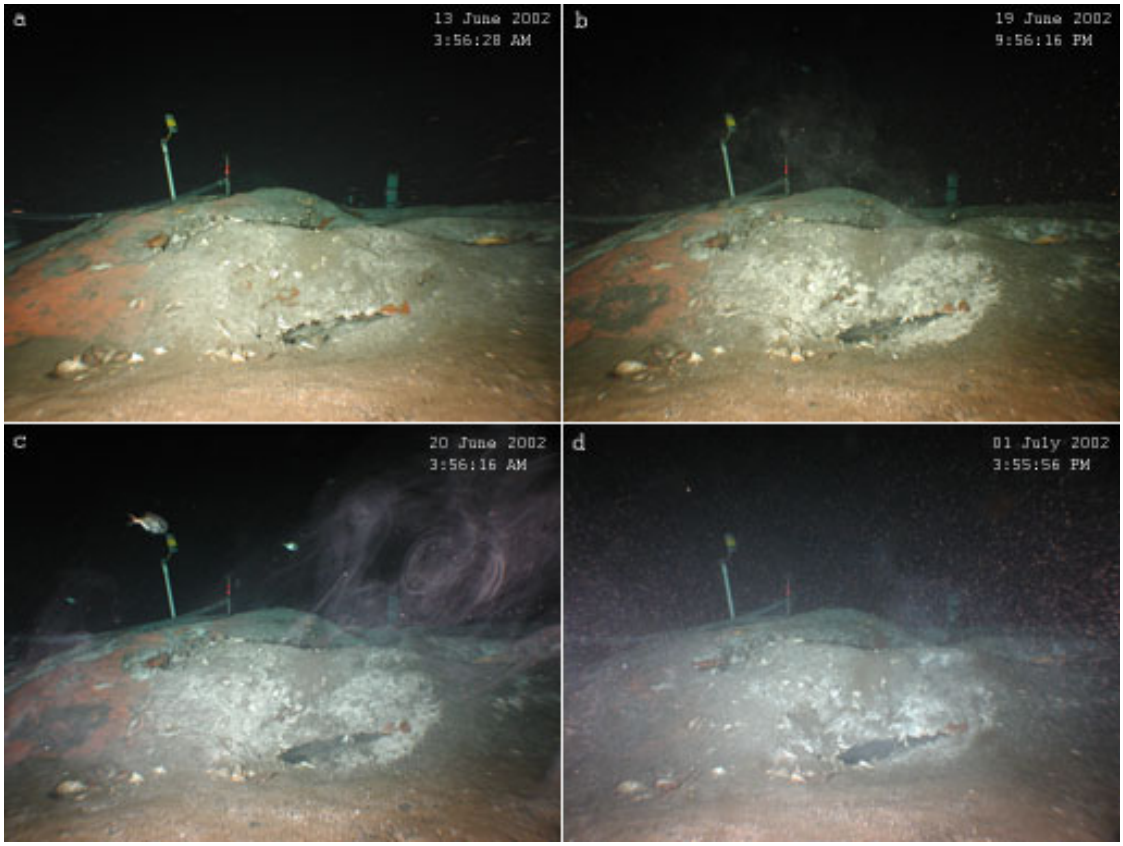

Fig. V-1. A time series of photographs of the gas hydrate outcropping illustrates the degrees of sediment resuspension observed at the site, from very little (a), to mild (b), to vigorous (c, d).

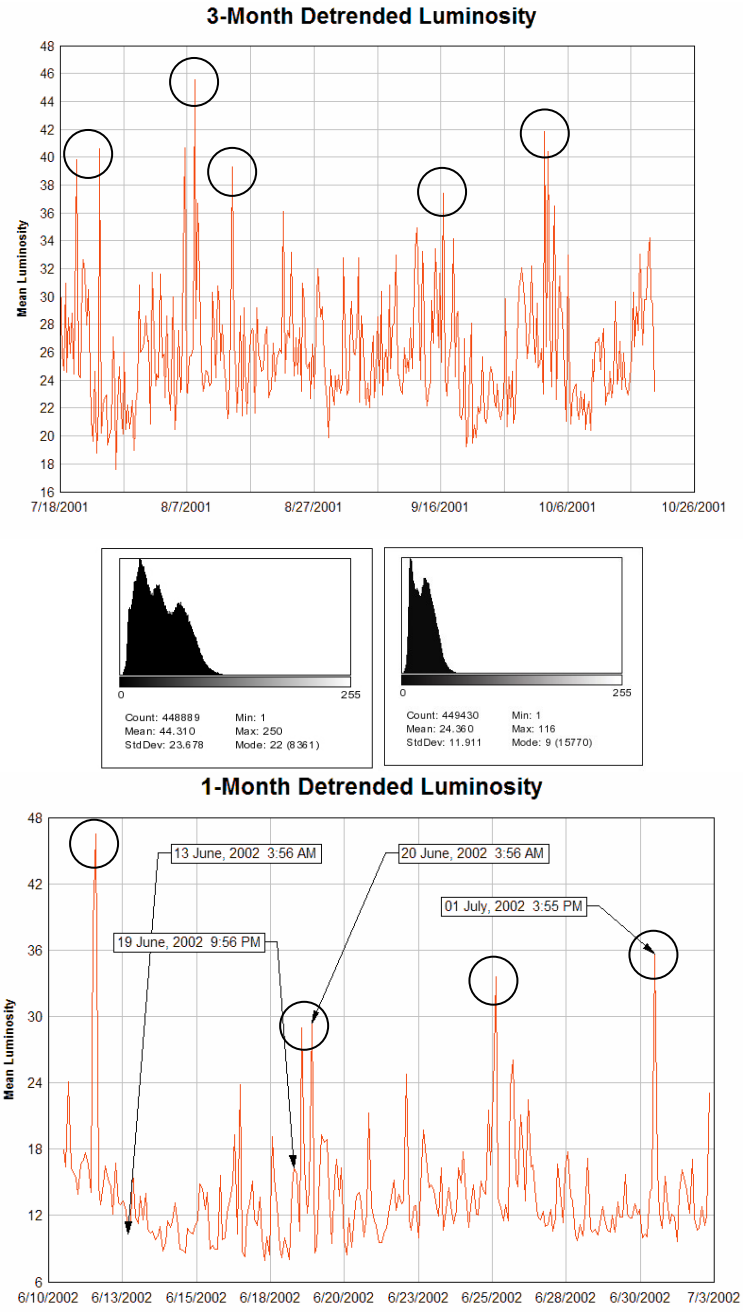

Fig. V-2. ImageJ® software was used to create histograms (center) of the visible portion of the water column and measure the luminosity. Higher luminosity (left histogram) indicated a lighter image and thus more particulate matter, while low luminosity (right histogram) indicated a darker image with less particulate matter. Both data sets were detrended to compensate for dimming of the camera lights due to battery discharge. The circled peaks are outlier high luminosity events. The labeled arrows indicate time-lapse images shown in the previous figure.

deployments, indicating tidal influences (Fig. V-3). Additional, higher-frequency tidal peaks were visible in the data from the year-long deployment. Although the turbulent events appeared to reoccur on a cyclic time scale, the power spectrum analysis showed no significant (>95% confidence) evidence of periodicity in the 3-month time-lapse record and a great deal of random noise. When some of the high-frequency noise was smoothed out of the 1-month time-lapse record a significant peak at the K1 period was revealed (Fig. V-4).

There was a great deal of variability in the strength of these occurrences in both records. Some sediment resuspension events were more powerful than others, lifting greater amounts of material and exerting more visible changes on the gas hydrate outcrop environment. The most extreme turbulence lifted detritus as large as 0.5cm in diameter into the water column and almost completely obscured the camera's field of view, resulting in outlier luminosity values that were 2 standard deviations above the mean. Such events were generally of short duration, only visible in a single time-lapse frame, such as those on 24 July, 6, 8, and 14 August, 30 September and 1 October, 2001 and on 12 and 26 June and 1 July, 2002. However, some of the events of intermediate power lasted for longer intervals. These occurrences only lifted smaller sediment particles into the water column and the luminosity values derived from the time-lapse images did not deviate as greatly from the mean. One period of intermediate sediment resuspension lasted 24 hours from 10 to 11 September, 2001, while another was maintained for 18 hours from 18:00 on 26 June to 12:00 on 27 June, 2002. None of the outlier events or longer-term occurrences correlated significantly with outliers or trends in the temperature data.

Discussion

Temperature probes and current meters in association with bubblometers that measure evolved gas have shown that as temperatures increase there is a corresponding increase in flow from existing bubble streams, and that upward temperature spikes are often associated with north/south currents (Roberts and Carney 1997). Although the thermal energy of these currents can have a major impact on the stability of gas hydrate, the velocity and force of the currents are generally not sufficient to suspend

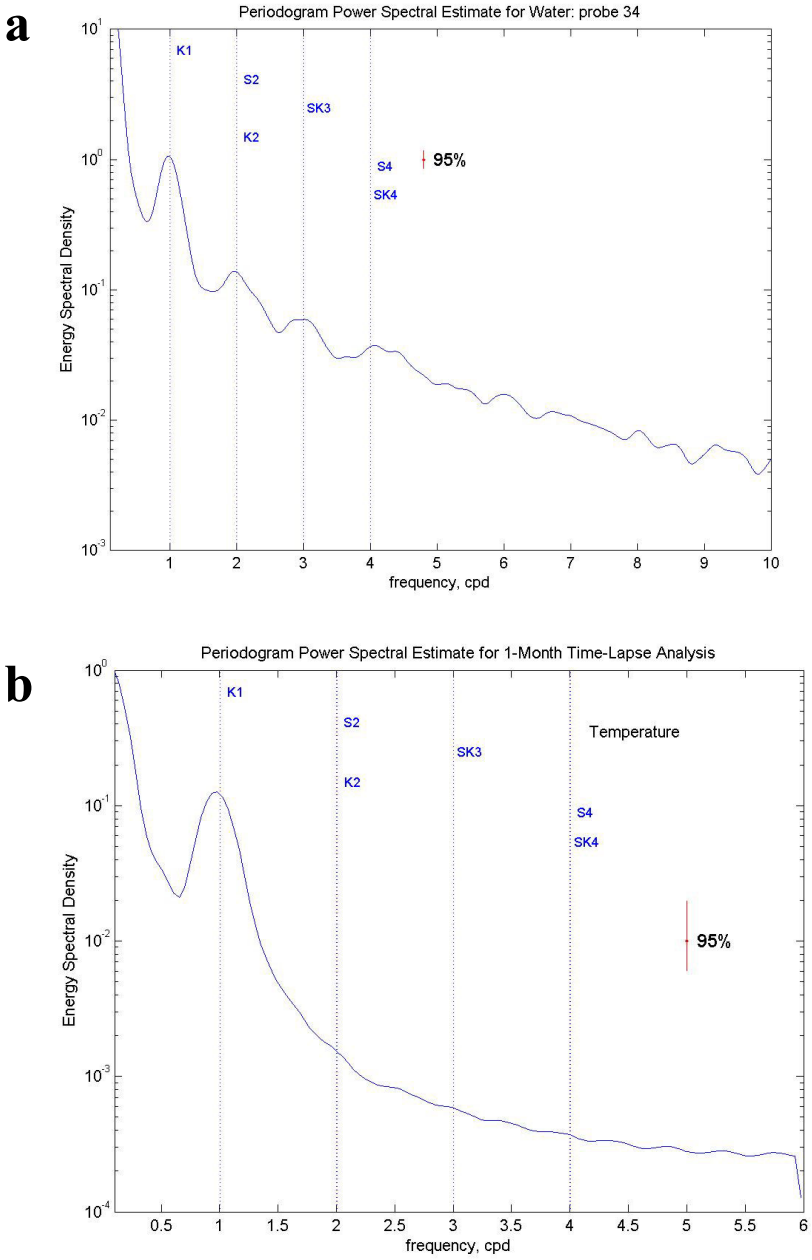

Fig. V-3. Power spectrum analysis of the temperatures recorded during the year-long (a) and 1-month (b) temperature probe deployment. A peak with significance greater than the 95% confidence interval is seen at the 23.9 hour (K1) tidal interval in both records. Additional, higher frequency tidal peaks (S2, K2, SK3, S4 and SK4) are visible in the data from the longer deployment.

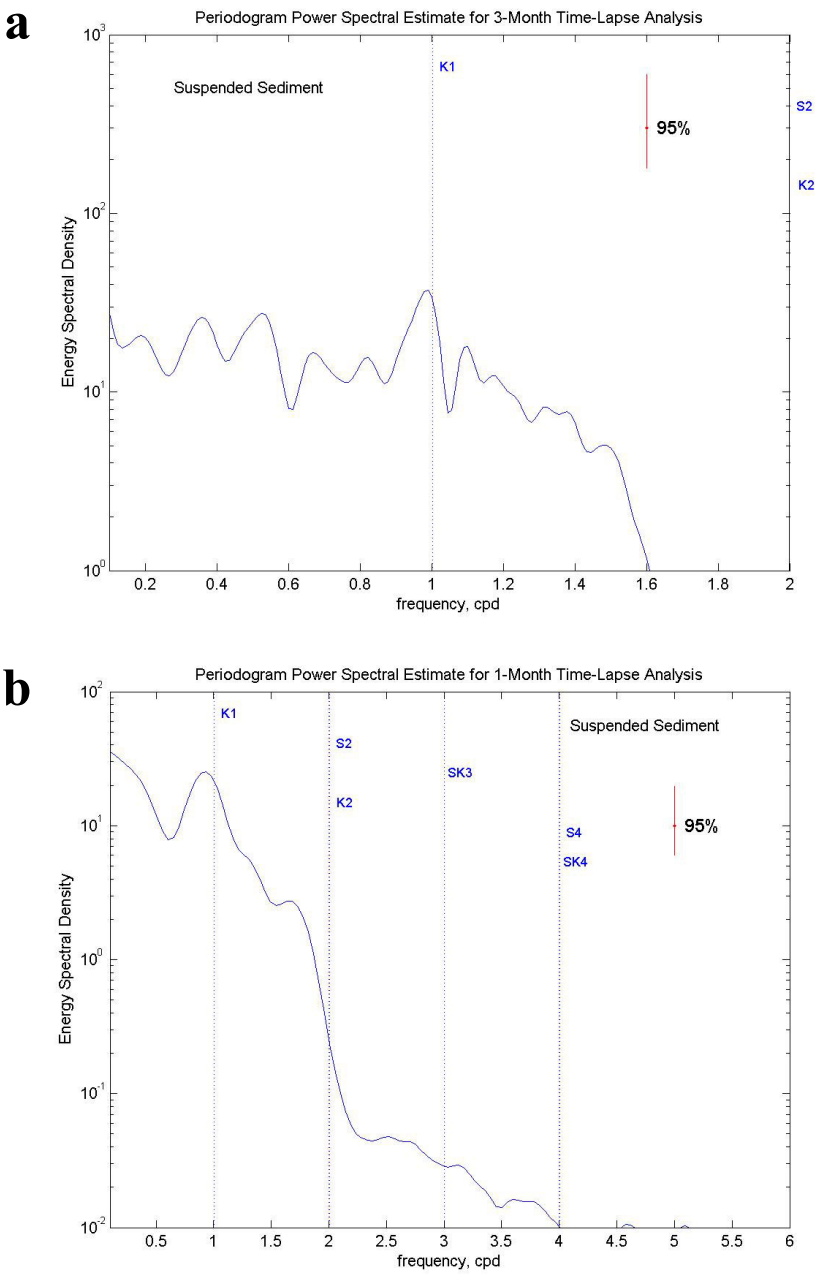

Fig. V-4. These periodograms chart the frequency of intense turbulent events observed during the 3-month (a) and 1-month (b) time-lapse records. The only peak greater than 95% significance occurs at the K1 interval, indicating some periodic tidal or inertial influence on sediment resuspension. The other, higher frequency peaks denote noise introduced by individual turbulent events that do not correlate with the tidal signals.

sediment or alter seafloor features in a direct way. Deep currents in the Atlantic and Pacific Oceans have been recorded at speeds of 50 cm/s and higher in marine canyons (Gardner, et al. 1984; Gardner 1989b). There are also records of benthic storms that cause enormous amounts of turbulence and resuspension at the sediment-water interface, even at 4000m depth, possibly due to the pressure changes and mass transport associated with surface storm systems (Gardner and Sullivan 1981). During a previous study in 1997 a current meter mooring was deployed in 547m of water at 27°46.95' N; 91°30.28' W, adjacent to the Bush Hill site (Guinasso 2001). Two Oregon Environmental Inc. 9407 vector-averaging current meters were attached to the mooring, one 10m above the bottom and one 300m above the bottom. They recorded a 10-minute average segment every hour for nine months. The results showed that currents were below 10 cm/s 93% of the time, and exhibited significant power spectrum peaks near 12 and 24 hours (Fig. V-5). Since the inertial period at this latitude is 25.7 hours the conclusion was that the daily peak could contain inertial as well as tidal signals. This appears to be a local effect, as an ADCP current meter deployed about 2km from the site during 2002 showed no significant peaks on a tidal or inertial interval. Occasional intensifications of the bottom currents were observed during ~1-2% of the CHEMO II record. These large fluctuations occasionally reached velocities of 10-20 cm/s.

When the shear stress exerted on the seafloor by bottom currents exceeds a critical value, determined by grain size, density, interstitial water, deposition history and bioturbation, resuspension can occur (Gardner 1989a). Based on calculations and experiments by Miller et al. (Miller, et al. 1977) and Young and Southard (Young and Southard 1978) resuspension of fine silt and mud of the type found at hydrocarbon seeps could occur at velocities as low as 11-12 cm s^{-1} (Gardner 1989a). If the organic detritus recently deposited by seep-dwelling organisms and the flocculent material produced by certain *Beggiatoa* mats are taken into account, the critical velocity could drop as low as 7 cm s^{-1} (Lampitt 1985). Given these low thresholds, and the added acceleration due to the topography of the gas hydrate outcrop, the current velocities recorded by the current meters adjacent to the site are strong enough to lift sediment into the water column. The rapid temperature changes that accompany the tidal currents could also affect resuspension at the seep site. It has been suggested that the density inversion created when cold water rapidly moves over warmer pore

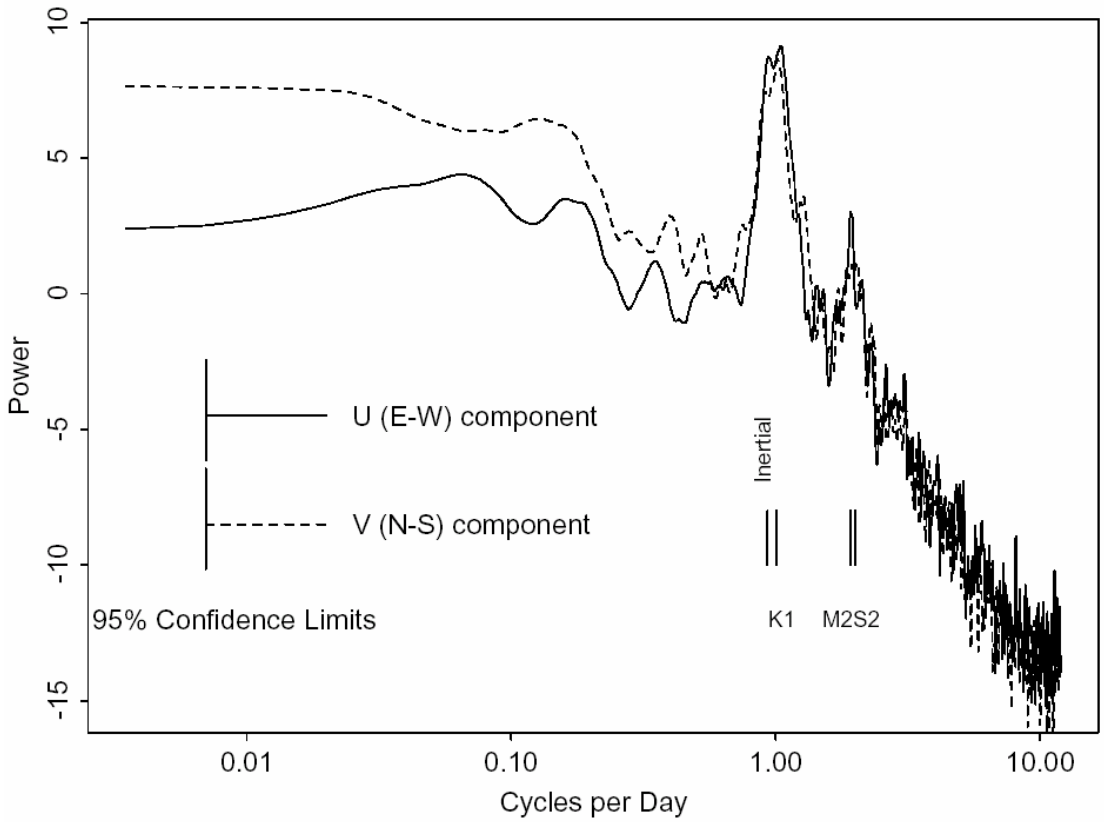

Fig. V-5. A power spectrum analysis of cycles of water movement recorded by the lower current meter deployed in 547m water depth adjacent to Bush Hill in 1997. Significant peaks were seen at the K1 (daily) and M2 and S2 tidal intervals, indicating a tidal component to the bottom currents. The similarity of the inertial current interval to the K1 tidal interval at this latitude means that the daily peak may include both signals (Guinasso 2001).

water in the sediment could promote resuspension of overlying sediment through buoyancy effects (Gardner 1989a).

The frequency peak that occurs at the K1 interval in both sediment suspension and temperature records suggests that tidal or inertial currents are at least one driving force that promotes sediment resuspension at this site. Low velocity currents could cause turbidity through acceleration due to local topography or strengthening by temperature inversions. However, there are many higher frequency sediment resuspension events that do not correlate with tidal intervals. These could be explained by intermittent bursts of higher velocity currents such as those recorded during 1997, which move at speeds of 10-20 cm/s and have sufficient power to suspend sediment and detritus. However, the highest levels of turbidity do not correlate significantly with any observed temperature maxima or minima that would suggest a major water movement event. Sediment can also be disturbed by gas hydrate decomposition or gas expulsion (De Beukelaer, et al. 2003; Leifer and MacDonald 2003), but these would also be preceded by an increase in temperature which was not present in the data. Another possible explanation could be intermittent fluid or gas venting unrelated to gas hydrate decomposition, which occurs in the area around the gas hydrate outcrop and would not require significant temperature increases. Because sediment disturbance at seep sites has a number of potentially significant implications, further study is required to determine the nature and causative agents of the resuspension events at GC 185.

The frequent sediment resuspension during the observation period indicates that the thickness and local distribution of surface sediments are subject to continuous, possibly rapid, change. Patches of exposed gas hydrate were often cleared of sediment cover following turbulent events, possibly increasing the rate of gas hydrate dissolution in those areas and contributing to crevice formation and gas hydrate mound colonization. The buoyant nature of gas hydrate, which is normally restrained by burial in sediment (Paull, et al. 2003), gives the redistribution of the sediment cap by water currents further significance. Once enough sediment is removed from the surface of the outcrop, and given the severe undercutting of the flanks, the entire feature could break free from the seafloor and rise into the water column, releasing massive amounts of gas as it dissociates.

Sediment resuspension events appear to be a major feature of the benthos at this site. The sediment-water interface is a vital environment for many benthic species and the location of most essential chemosynthetic and oxidation reactions. Disruption and reorganization of this interface could have significant impact on the biochemical processes of the seep community. Sediment resuspension due to water movement could also increase the availability of food for filter feeders, transport the organic material produced by gas hydrate mound communities beyond the immediate vicinity of the seep, distribute bacterial cells from site to site, aid in the larval dispersal of seep organisms, and assist in the burial of tube worm roots that is necessary for their sulfide uptake. The wide range of possible effects these turbulent events could exert on the biology and geology of the gas hydrate outcrop make them one of the most important environmental processes observed at this site.

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH

Conclusions

Although the temperatures recorded during this study reached levels sufficient to destabilize gas hydrate, there was no major change in shape or size of the gas hydrate outcropping being studied. This indicates a higher degree of stability than laboratory studies or prior *in situ* observations have shown. Sediment distribution on the surface of the outcrop and the undercutting and crevices on the flanks and base of the mound indicate that the mound forms below the sediment surface and is pushed upwards over time. The deposit of gas hydrate monitored during this study is a stable component of the deep Gulf of Mexico seep environment over time scales of months.

The relatively high density and diversity of organisms observed at the mound suggest that gas hydrate outcrops provide an aggregation point for deep-sea organisms. The range of trophic levels seen at the site provides an attractive source of food for many species of deep Gulf of Mexico predators. Large, naturally occurring crevices at the base and flanks of the gas hydrate mound appear to provide shelter for numerous small seep organisms and may be excavated by biological activity. The relatively stable topography of the gas hydrate mound combines with high organic output and sediment turnover to make the seep site an ideal habitat for deep sea organisms.

The frequency and recurrence of sediment resuspension indicate that change in the depth and local distribution of surface sediments and the reduced chemicals contained therein is a prominent feature of the benthos at these sites. Patches of exposed gas hydrate were often cleared of sediment cover following turbulent events, possibly increasing the rate of gas hydrate dissolution in those areas and contributing to crevice formation and gas hydrate mound colonization. The importance of the sediment cover in counteracting the buoyancy of gas hydrate increases the significance of any thinning of the sediment layer. Because the sediment interface is a critical environment for hydrocarbon oxidation and chemosynthesis, short term variations and heterogeneity may be important attributes of these settings.

Future Research

The success of the time-lapse camera deployment and the amount of data recovered confirms the value of the technology, and should lead to future deployments of similar arrays. Cameras recording over longer durations and capturing images at more frequent intervals would provide a more detailed record of temporal processes at deep-sea seep communities. Attached temperature probes, current meters, ADCPs, pressure sensors, and light meters would assist in documenting the environmental processes that occur. Multiple arrays should be deployed at the GC 185 site to observe the gas hydrate outcrop from all angles and obtain a 3-dimensional record of temporal changes at the site. Cameras should also be deployed at other gas hydrate sites in the Gulf of Mexico and seep sites worldwide to document any differences in the processes that occur and to compare the biological activity at these sites. Time-lapse sensor arrays should be positioned at non-seep background sites as well, to obtain control data. One possible experiment could involve time-lapse observations of a carbonate rock deposit or an artificial object that is the same approximate shape and size as the gas hydrate outcrop. The resulting data would determine whether the observed sediment resuspension events were influenced by local topography or were a result of some other process unique to the gas hydrate mound. The unexpected longevity of the gas hydrate outcrop, the high degree of biological activity at the site, and the frequent sediment resuspension events are features that require further observation and study.

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Sept. 1998 – May 2001	UNIVERSITY OF PENNSYLVANIA College of General Studies • Philadelphia, PA
Sept. 1994 – May 1998	GEORGETOWN UNIVERSITY College of Arts and Sciences • Washington, DC *BS, Biology Major, Psychology minor, May 1998* Thesis: *Biodiversity in the Marine Abyss*

Publications and Presentations

Vardaro, M.F., Bender, L.C. and MacDonald, I.R. (2003) Long-term measurement of sediment resuspension and gas hydrate stability at a Gulf of Mexico seep site. Eos Trans. AGU. 84(46) Fall Meet. Suppl., Abstract OS51B-0859.

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